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THESIS

A REVOLUTIONARY APPROACH FOR THE DEVELOPMENT OF FUTURE GROUND COMBAT SYSTEM SPECIFICATIONS

by

Tobias Treml

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13. ABSTRACT (maximum 200 words)

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A REVOLUTIONARY APPROACH FOR THE DEVELOPMENT OF FUTURE GROUND COMBAT SYSTEM SPECIFICATIONS

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ABSTRACT

This thesis provides a new specification development process for Ground Combat Vehicles (GCVs). The most recent development programs for such a vehicle class failed due to extensive cost overruns. The author uses agent-based simulation to model and study the impacts of CGV capabilities in a most likely combat scenario according to the current threat assessment of the U.S. government. The most advanced modern weapon systems are used as a baseline performance and extensive research is done to determine the state-of-the-art technologies available. These experimental technologies are then transferred to feasible ranges for specified performance factors for GCVs, such as engagement range, weapon’s lethality, armor, and mobility. Nearly orthogonal and space-filling designs are used to efficiently construct a response surface consisting of defined measures of effectiveness (MOEs) for GCVs. For each MOE, a meta-model is fitted that includes the most significant factors, interactions, and non-linarites. These models are then combined to find the most “robust” solution since a model will never exactly depict the real situation and a GCV will not be deployed in a scenario exactly like the one used in the study. The results of the meta-models will be used by the Department of Systems Engineering at the Naval Postgraduate School to create a “dashboard” for visualization of the tradeoff effects between performance factors.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGS	*Awtomatitscheskij Granatomjot Stankowyj,* (heavy grenade launcher)
APS	Active Protection System
AWARS	Advanced Warfighting Simulation
CAPE	Cost Assessment and Program Evaluation
CAS	Close Air Support
CHAMP	Counter-electronics High-powered Microwave Advanced Missile Project
DF	Degrees of Freedom
DOE	Design of Experiments
DTA	Defense Technology Agency
EW	Electromagnetic Warfare
FARP	Forward Arming and Refueling Point
FCS	Future Combat Systems
GA-EMS	General Atomics Electromagnetics System
GCV	Ground Combat Vehicle
GUI	Graphical User Interface
HBCT	Heavy Brigade Combat Team
HEL	High Energy Laser
IED	Improvised Explosive Device
IHS	Information Handling Services
MANA-V	Map Aware Non-Uniform Automata-Vector
MANPAD	Man-Portable Air-Defense System
MAW	Marine Air Wing
MILAN	Missile d´infanterie Léger Antichar
MOE	Measures of Effectiveness
NBC	Nuclear, Biological, Chemical
NCW	Network Centric Warfare
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School

LOS	Line of Sight
RFP	Request for Proposal
RHA	Rolled Homogeneous Armor
SAM	Surface to Air Missile
TOW	Tube-launched, Optically-tracked, Wire-guided
TRADOC	U.S. Army Training and Doctrine Command
UAV	Unmanned Aerial Vehicle

EXECUTIVE SUMMARY

Since the cancelation of the Future Combat Systems (FCS) program in 2009, there has been increasing criticism of the follow-on Ground Combat Vehicle (GCV) project and the observed difficulties in many ground combat system acquisition efforts conducted internationally. The question arises as to whether there is a better way to determine the specifications for such a system, and, if so, how these specifications can be adapted when changes become necessary. The purpose of this thesis is to provide decision makers with additional information to enable them to reduce the cost and time of such an acquisition project while enhancing the overall performance of the end system. The author suggests that the following analysis be conducted before the specifications of a GCV are fixed and whenever these specifications are changed:

1. Perform an analysis to determine the scenarios in which the new system will most likely be deployed, and what measurements of effectiveness (MOEs) it must achieve. Critical thresholds and the weighting of the MOEs must be defined for this analysis.
2. Use these scenarios to set up a combat simulation. It is important to study the GCV in context with already existing combat systems as there are interactions between the different systems. The study detailed in this thesis uses Map Aware Non-Uniform Automata-V (MANA-V) as it is an agent-based simulation which not only models human behavior, but also is capable of replicating numerous scenarios in a reasonable amount of time. MANA-V has a steep learning curve as well as a capacity for data farming, and most important, it is designed to get quick insights and identify major dependencies. The drawback of MANA-V is that the physical resolution is low.
3. Define the ranges of the possible specification parameters according to subject matter experts, battlefield experiences, field studies, and literature research; and combine them into a design of experiment (DOE). This study uses a Nearly Orthogonal Latin Hypercube (NOLH) design. The advantage is that NOLHs allow you to efficiently explore the whole range of the 14 input parameters with only 65 data points in a reasonable timeframe.
4. Run the simulation with a calculated number of replications to achieve the desired resolution. Here, a casualty rate of ±1 per

battle is the desired resolution. This leads to 460 replications per design point to achieve a statistical power of 0.9. After the experiments are conducted, collect the output data on the MOEs.

5. Analyze the data with different statistical tools to identify the most influential factors on MOE performance. The tools used in this study are regression models and partition trees. The regression models are divided into main effect models and models which allow for interactions between the factors as well as non-linearities. The analysis is done for each MOE separately.

6. Select the best models during the analysis process to create a meta-model for each MOE which describes how the MOE changes with changes of the input factors. For example, if a factor such as armor is changed, how does it affect the expected casualties of the GCV and the whole deployed force?

7. Conduct an analysis of the meta-models to find the most important factors for each MOE, their interactions, and the tradeoffs between them. The variability of the result must also be considered because a higher uncertainty of the results reduces its benefit. A specification process must aim for a “robust” solution since the scenarios will not be the actual deployment, and the simulation does not fully represent the real situation. Insights for specifications, tactics, and the necessary force structure must be identified.

It is planned that the results of the meta-models developed in this research will be the input to create a “dashboard” for visualization of the tradeoff effects between factors.

Major Conclusions:

- The approach detailed in thesis is feasible for land-based systems. The most influential factors for each MOE can be identified and explained. The approach cannot guarantee an optimal solution, but it can give additional insights and direct research for the specification finding.
- Interactions and non-linearities are influential and must be considered to estimate the performance of the GCV for a given scenario.
- Survivability of the GCV is a result of different factors which all interact and can therefore be difficult to predict with conventional methods.

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I. INTRODUCTION

The “Future Combat Systems” (FCS), a family of 18 manned and unmanned networked ground combat vehicles and one of the most ambitious programs for army modernization ever, failed in 2009 after the U.S. Army spent $19.9 billion in development and research (Billion Lexington institute, 2012). No system was built for this money. The official reason for this failure was that the FCS could not deal with the evolving threat of improvised explosive devices (IED) in Iraq and Afghanistan as these combat systems were designed as light-armored, highly mobile platforms. FCS’s major advantage was superior situational awareness which would enable it to destroy the enemy before he ever could get within reach of his target. This was simply not possible with IEDs and an adapting enemy. As one involved soldier said, "Of course, the problem with this approach is that if you're hit, you die" (GlobalSecurity, 2012).

The army took the lessons learned in the follow-up program, the “Ground Combat Vehicle” (GCV) (Erwin, 2011), which is a program consisting of only one vehicle, an infantry carrier for a full squad of nine soldiers and the crew. Two major development contracts were issued to BAE Systems and General Dynamics Land Systems after the program had been revised in July 2011. The specifications for the GCV for survivability led to a behemoth vehicle (72 tons for an infantry carrier in the BAE prototype version), which would almost certainly be difficult to deploy, costly to maintain, and unaffordable given the fact that weight is one of the major cost factors for estimating the price of a combat vehicle (Feickert, 2013). So, it is not surprising that the Cost Assessment and Program Evaluation (CAPE) organization estimated the price per vehicle to be $16 to $17 million rather than the desired $13 million (in FY2011 constant dollars). While the weight of the General Dynamics prototype is not yet known officially, a working paper for the Congress issued in November 2012 lists the GCV of Dynamics Systems at 64 tons in a basic version, with a potential maximal weight of 74 tons. The maximum weight for the BAE system is stated at 84 tons (Feickert, 2013).

The historical development of U.S. armored vehicles is shown in Figure 1.

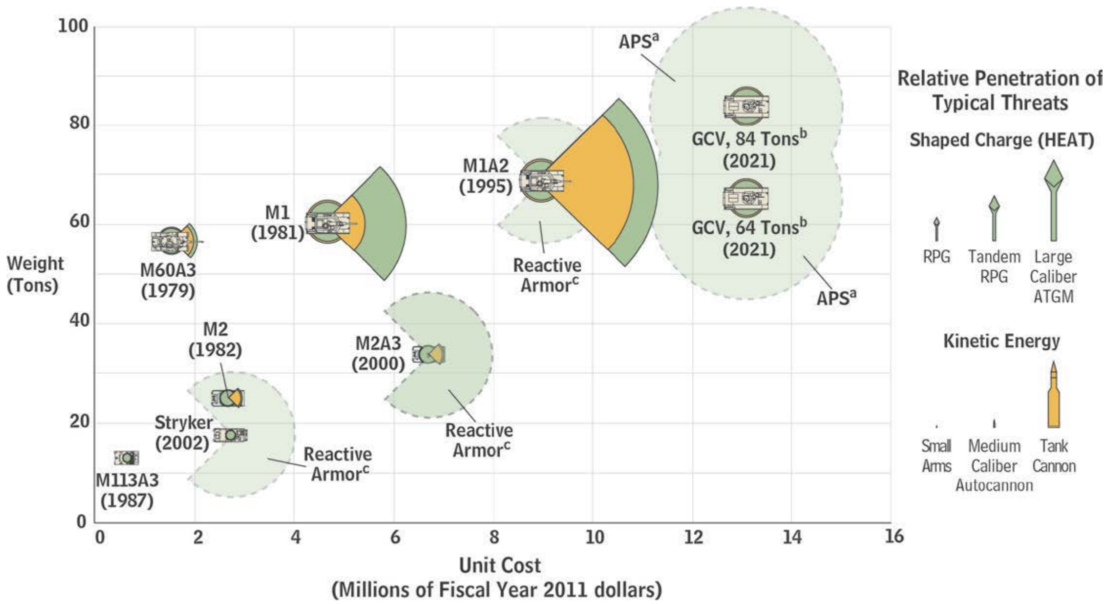

Figure 1. Evolution of armored vehicles in the U. S. Army (Cost, weight, and protection). The colored sectors show the relative protection levels of equivalent steel rolled homogeneous armor provided by the vehicles' base armor. Relative top and bottom protection levels are not shown in this figure. All vehicles except the Ground Combat Vehicle (GCV) have minimal protection in these areas. The GCV specification requires increased protection for top and bottom. Vehicle icons are shown to scale. None of the active protection systems proposed for the GCV will provide protection against kinetic-energy rounds (From Kempinski & Murphy, 2012).

Another key consideration for a heavyweight vehicle is that its tactical mobility is constricted due the maximum weight class of bridges and the damage done to roads. This is a major concern, especially in less developed countries and in urban terrain, exactly the environment that is considered to be the most likely area of operation in the future. A National Security official stated in a Congressional paper dealing with the GCV, "[a] large vehicle is not only difficult to transport to the theater and consumes more fuel, it also damages roads and bridges and has trouble traversing narrow urban streets, creating problems in peacekeeping and counterinsurgency” (Kempinski & Murphy, 2012). These facts, together with expected cuts in the defense budget, led to the conclusion that changes in the specification of the GCV or even a reset of the whole program are necessary.

In a time when an ever-faster changing security environment drives an even faster adapting threat for deployed forces, it is most likely that changes will occur in every major defense acquisition project. As the current specification process is not designed to react quickly to new requirements, it leads to the impression that there are basic flaws in the acquisition process of military ground systems. From the experiences of the author in the German Army and the literature research for this thesis, it has become clear that the acquisition process is not only a problem for the U.S. forces, but an international one. Therefore, the question arises: What can be changed to make the specification process better?

Currently, specifications are drawn from experience obtained in actual battles and exercises, then set by subject matter experts, and approved by a program manager (U.S. Department of Defense, 2003). In the case of the current GCV, the U.S. Army set 744 specifications in its request for proposal (RFP), where they defined protection against specified threats, the number of soldiers and equipment to be transported, and so on (Kempinski & Murphy, 2012).

Farther along in the acquisition process, the specifications are assessed by simulations dealing with potential future scenarios and field tests. These specifications are aggregated into parameters like lethality, maneuverability, or sustainability. If a parameter specification is not met, changes may be brought into the program with corresponding delays and cost increases. After the next validation, it may be seen that these changes caused problems in other requirements. For example, if survivability is a major concern, then usually more armor is added. It is easy to see that “hardening” the system increases survivability; however, maneuverability will decrease as a heavier system is slower and might even no longer meet the requirements for cost or air transport.

Less maneuverability might also decrease survivability again. Even if all the specifications and changes are decided by the most experienced subject matter experts, it can be seen that the number of specifications is just too high to keep all interactions in mind, and with hundreds of specifications it is just not possible to define the whole system such that a contractor will build a vehicle with the desired overall performance. For example, on their defencetalk homepage BAE stated, “Unfortunately, the Pentagon didn’t specify a weight limit in its Request for Proposal (RFP), so the GCV came out a bit on the heavy side” (BAE Systems Releases, 2012).

This is not a new problem as, for example, German “tank” development in World War II showed the same pattern. To make tanks more survivable the Germans developed the “TIGER” model which had heavy armor, but it could not uphold previous maneuverability. As German scientists and military leaders recognized the weaknesses of the “TIGERS” they developed a more balanced one—the “PANTHERS” series—which is recognized as the best performing tank of the war, even with less armor (The Armed Forces Military Museum, 2013). To deal with this development pattern a better approach must be developed.

If one analyzes the problem framework, he will find that what a system has to achieve is not a certain speed or armor class, but certain measures of effectiveness (MOEs)—such as the probability of mission success and expected loss rate under most likely conditions.

For this reason, the specification process of a weapons system must do the following:

- Define major characteristics of the system.
- Define the most likely scenarios where the system will have to perform.
- Define measures of effectiveness.

The mission-based approach is especially important as the available force structure in a scenario heavily influences the performance requirements of a system. For example, if an analyst would use a battle between an enemy and a homogeneous main battle tank force he would find that an increase in the weapon range would give the tank force a huge advantage in performance according to MOEs such as lethality and survivability. But, what if the scenario includes long-range artillery weapons or the terrain would only allow medium combat at small distances? Here, the benefit of an increased weapon range would be severely reduced. So, it is critical to define the most likely scenarios as well as possible stressing scenarios first.

After the above three steps are performed, the combat system should be modeled with a reasonable range of the “normal” specification parameters. These ranges are then used as input parameters to perform combat simulations within an adequate modeling environment. A sophisticated design of experiments (DOE) can be used to efficiently explore the different combinations of parameter values and their expected variance (Kleijnen, Sanchez, Lucas, & Cioppa, 2005).

Once the experimental data is obtained, statistical regression can be used to identify the most important input parameters in regard to the MOEs and their interactions. This “response surface” is usable to create a meta-model in which the tradeoffs between the specification parameters can be visualized. A “meta-model” is defined in this thesis as an abstract relationship between the MOE and the input parameters for the combat simulation in the form of a regression model. The results can be applied by engineers to design the physical specifications of a system, such as speed, armor, sensors, and so on.

The end state of this process is that decision makers can immediately see what a change in one specification means for the envisioned project and therefore helps them to find the right decision without getting surprised.

So, the described process can be applied at the following points:

- When designing the specifications for a new system.
- Whenever changes must be introduced into the program, program managers can immediately visualize tradeoffs and therefore decide which factors changes must be made while still achieving all MOEs.

A. OBJECTIVE STATEMENT

Future ground combat systems will have to fulfill complex missions in a variety of different scenarios throughout the full spectrum of modern warfare, including asymmetric scenarios. This fact makes it especially difficult to find the right mix of capabilities as the next mission and the corresponding circumstances (like enemy, terrain, climate, and so on) remain uncertain. Therefore, for future weapon specification processes, the question is not to get it right, but much more to get it close and robust enough. This research provides data, results, and insights for an alternative, more flexible approach to the specification process.

B. RESEARCH QUESTIONS

The thesis research is guided by following questions:

- Which factors contribute most to defined MOEs in a given scenario?
- Must interactions be considered in the specification process?
- Must non-linearities be considered in the specification process?
- Which factors other than armor are major contributors to ground combat vehicles survivability and are they quantifiable?
- Can the specification process for ground combat systems be improved and made more flexible with the new approach?

C. BENEFITS OF THE STUDY

The desired benefits of the whole project include the following:

- Improvement in finding and altering the process for specifications of GCVs.
- Instantaneous visualization of how changes in one specification requirement influence other requirements.
- Provision for more fact-based discussion in development and change of specification requirements—especially important for joint and multinational projects.
- Provision for non-trained personal to visualize tradeoffs between specification factors and the impact of design changes.
- Improvements to the specification process that reduce costs and raise the level of performance and robustness for future ground combat systems.
- Enlargements that could be taken to create a “dashboard” for defining the requirements of whole task forces and force structures.

D. METHODOLOGY

The thesis divides the research into seven phases (see Figure 2).

- Define the MOEs for future ground combat systems and their critical thresholds.
- Program realistic scenarios in the MANA-V environment in which current systems have to operate as a reference for the performance of future systems.
- Use DOE and data farming techniques to create ranges in the specification parameters of future systems.
- Run simulations according to the design and collect output data.
- Analyze the results to identify the most influential factors and their interactions according to the MOEs and the scenarios.
- Use regression techniques to create meta-models.
- Analyze the meta-models and find the most important factors for achieving the MOEs and tradeoffs between them.

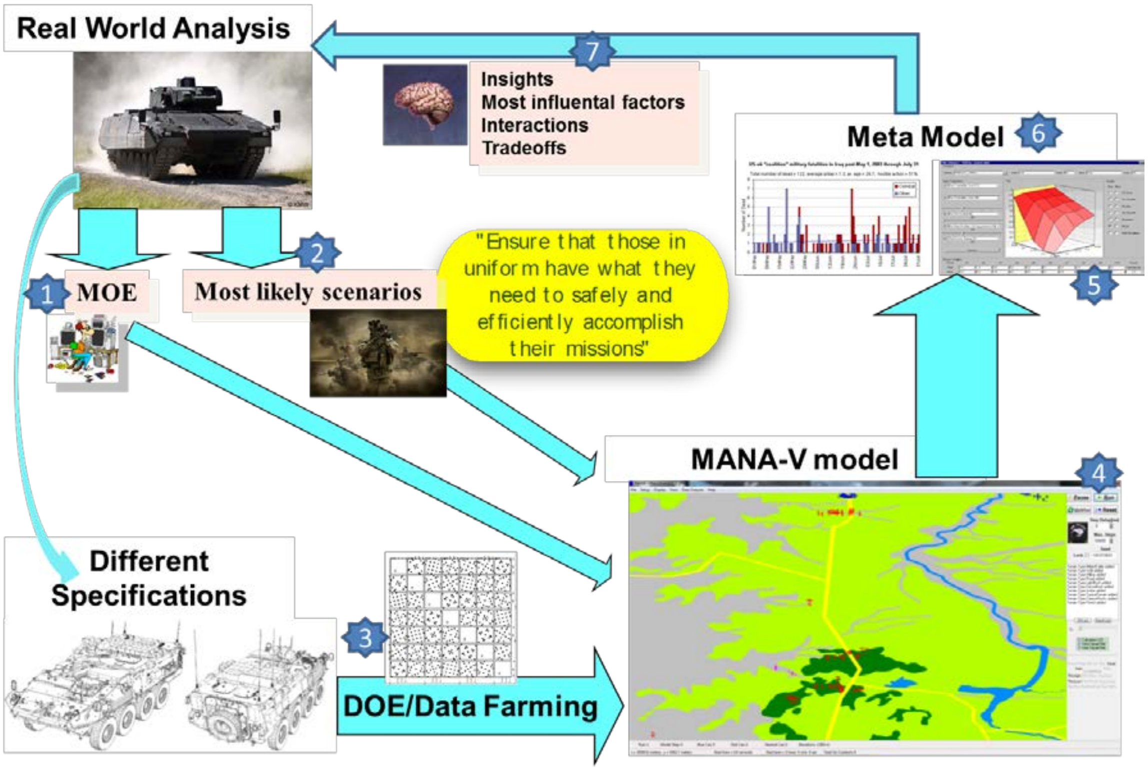

Figure 2. Graphical process structure of the research thesis.

The results will then be given to the Systems Engineering Department for further use in the creation of the first land combat system "dashboard."

E. PREVIOUS RESEARCH

A similar approach has been used for the design of Navy ships at the Naval Postgraduate School (NPS) in cooperation between the Operations Research Department and the Systems Engineering Department. The feasibility of this specifications approach for surface vessels had been demonstrated by three theses in the Systems Engineering Department, the results of which were combined into the first version of a visualization tool called a "dashboard." Welch (2011) and Fox (2011) did the basic work with single surface warship scenarios, which then were combined by Bahlman (2012). They developed a prototype of the so-called "dashboard" with the goal of enabling users to visualize the tradeoffs of the specification factors in terms of feasibility. They implemented engineering design knowledge for constructing ships with the requirements for fulfilling the defined scenario MOEs (Fox, 2011; Welch, 2011; Bahlman, 2012).

The conducted theses showed that the approach itself was beneficial for constructing better ships and allowing decision makers to visualize the tradeoffs between design factors. The major differences between these theses and the current study occur in the more complex environment for land systems, the more complex approach to considering force structure interactions, and the focus on a combat scenario. The current study also differs in testing for interactions between the input parameters and for non-linearities.

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II. SELECTION OF THE INPUT PARAMETER RANGES

As this study deals with specifications of future ground combat systems and uses DOE techniques, two questions must be answered:

- What are the input parameters that most influence the performance of the GCV according to the MOEs?
- What are reasonable ranges for each of these parameters according to possible future technology developments?

The next chapter answers both of these questions. Note that whenever future technology or new untested compositions of mature technologies are used there is a probability the actual performance of the subsystem may be worse than its approximate performance in previous tests outside the vehicle.

1. Selection of Input Parameters

The answer to the first question has two aspects. It is not only what influences the performance of the system in the scenario, but also whether these parameters can be changed in the MANA software used in this research. When factors cannot be set directly, it is often possible in MANA to adjust the scenario in an indirect way.

For selecting possible input parameters, extensive literature research and the author's own experience as a subject matter expert for armored land warfare are used. However, a more comprehensive way would be to employ a systems engineering design process that would provide both, functional system architecture and physical system architecture. The functional architecture links the top level system functions to lower level functions and desired capabilities as well as to appropriate metrics, specifically measures of performance (MOP). A recent capstone project, conducted by a group of U.S. Army civilian master's students in the Systems Engineering department, developed a functional architecture for the GCV as part of a mixed maneuver company of tanks and GCVs (Vehicle Survivability Team & Cohort 311-114G, 2013). Their very detailed list of system functions are easily translated into possible model parameters (see Appendix A). A more narrowly list is used in this thesis because it focuses on the main factors and because of the restrictions in MANA (McIntosh, 2007). The list is divided into three major performance characteristics of ground combat systems and supplemental factors:

a. Lethality

- Sensor field-of-view
- Sensor range
- Sensor quality
- Main and secondary weapon range
- Main and secondary weapon precision
- Main and secondary weapon penetration/effects
- Communication/Information/Networks

b. Mobility

- Speed on different surfaces
- Acceleration

c. Protection/Survivability

- Long range engagement
- Concealment
- Avoid being hit: ”Soft and Hard Kill” Systems
- Armor

d. Other

- Robotics

A comparison of the given list with the list in Appendix A shows that MANA forced the author to reduce the considered input parameters, but this approach provides clear relationships between the major contributing factors. Further studies and other software may be used to consider the basic factors in more detail.

2. Selection of Parameter Ranges

To make a good estimate of what will be possible in the future, the author chose to use the advertised benefits of new technologies for GCV by the most important producers of land combat systems. From the experience of the author, the suggested performance of these technologies is nearly always overestimated as the companies have interests in selling their products, or the performance is reduced by additional restrictions imposed when a subsystem is integrated into the combat vehicle. Therefore, it is possible to design the upper bounds of the input parameter by using the official stated performance parameter of the new technologies. It is the author's hope that this literature review will be a very helpful overview for future research in the specification process. The websites of the following contractors have been used as a base, and follow-on research has been conducted in various Internet sources: Rheinmetall, BAE, General Dynamics, SAIC, Textron Systems, Nexter, Renault, Uralvagonzavod (Defense Update, 2013)**.**

a. Lethality

Sensor Field-of-View

For the modeling restriction some agents have been modeled with 360 degree sensors. In reality, many systems are not deployed in urban terrain due their lack of overview and their blind spots—which have proven a major disadvantage in urban and close range combat.

Modern developments for GCVs are now able to address this capability gap and provide an armored vehicle, such as theT90MS and the Israeli infantry carrier "NAMER," with "see-through armor" optics providing the crew with a 360 degree view around the vehicle. This capability is provided by electro-optical observation and sighting systems. Drawbacks of the systems are that the optics are vulnerable to enemy fire and are often not capable of thermal or night vision. Both of these issues can be addressed and are said to be solved by the producer. Another unsolved aspect is that the crew of a combat vehicle is still human and, especially if the tendency to reduce the crew to only two people is applied, has limited information processing power. It will be difficult to handle all the additional information of a 360 degree view together with the view of the already established main sights and the normal workload like communications, navigating the vehicle, loading the appropriate ammunition, engaging the correct target, and so on. Therefore, the crew-size must be considered while equipping a vehicle with sensors. Crew size will influence the volume to be armored and workload to be done. That a 360 degree field-of-view is feasible can be seen in current aircraft where a similar workload must be processed. Most current developments for the GCV use 360 degree field-of-view and a three-man crew design (Defense Update, 2010).

Sensor Range and Quality

As technology in the electro-optical area is fast developing, nearly every year new and more sensitive sensors become available. With new image detecting software, identification and classification of unknown contacts can be improved or automated. As vehicle-based sensors advance, data networks also enable other solutions with external sensors for GCVs (Night Vision and Electronic Sensor Directorate NVSED, 2013).

Another enabler for battlefield reconnaissance is the use of *unmanned aerial vehicles* (*UAVs*) based on ground combat vehicles. The FCS is designed for using UAV technology and embeds it in a network structure for real time targeting information. In the given scenario there is already a UAV “RAVEN” agent modeled so the effect of a vehicle-based UAV will be diminished even when additional UAVs could provide more information. The author chose to model the effect of close range UAVs on a vehicle by simply increasing the sensor capabilities of the vehicle agents. Additional studies could be conducted to look at the effect of micro UAV swarms on the MOEs by actually modeling each UAV (GlobalSecurity, 2013).

A relatively new improvement to the surveillance capabilities of ground combat systems is the use of *unattended ground sensors*. Here, many automated sensors are distributed in a certain area by hand or by artillery. These sensors transmit detections to the base station, which is in the ground vehicle, and provides for an accurate picture of the battlefield in areas beyond the reach of even the most sophisticated GCV sensors (Textron Defense Systems, 2013).

Further improvements for surveillance can also be achieved by using the benefits of *network centric warfare* (NCW); NCW is the combination of ISR, command and control, and effectors in one information space. The idea is that every participant of the network has access to all information which is relevant for his mission. The U.S. forces use the approach of a Global Information Grid, which means that dispersed participants all over the world have access to one combined information pool. Of course, there are still many criticisms, uncertainties, misunderstandings, and developments that will occur until such a project can be successful, but right now most Western nations have their own version of NCW under development. In the existing force structure the beginning of this concept is being realized. For example, a targeting process for a detected air defense system in Operation Desert Storm took days. In Operation Iraqi Freedom it was a question of minutes due to better information networks. Therefore, the author chooses to implement such a “global” information system in the agent-based model described in this thesis. The effects can be increased from the current state until every Blue agent has access to all information about Blue and Red forces instantaneously (Alberts, 1999; Wilson, 2007).

Main and Secondary Weapon Ranges, Precision, Penetration Capabilities

A *High Energy Laser (HEL)* can be used in the future as the main or secondary weapon system, as well as an air-defense counter rocket, and anti-artillery defense system. New developments are reaching the point where the HEL weapon combined with a corresponding sensor system (mostly radar) is small enough to be installed on ground combat vehicles. The question will be how well they can perform under combat conditions which include all kinds of weather disturbances and electronic interference.

In their use as main weapons, the HEL has the potential to accomplish a nearly 100% hit probability as all the dispersion effects for ballistic projectiles no longer apply. The author is able to judge this from his own experience as he used laser range finders on main battle tanks for 10 years, and the difference is only the intensity of the laser beam used. The problem is that an HEL needs a lot of energy, and the penetration capability decreases very quickly with increasing distance. As there is no solution approximated for this problem its use as a main weapon system is not examined in this study. The use of HEL as a defense weapon against rockets, airplanes, and indirect fire shells as well as blinding sensors is realistic in the near future. For example, Rheinmetall will start integrating such systems in ground vehicles in 2013 (T. Eshel, 2012a; Defense Update, 2011; N. Eshel, 2011).

Rail guns are considered to be a promising new gun family for naval ships, and in the near future minimization efforts could make a vehicle equipped with a rail gun possible. Today, rail guns struggle with the same difficulties as laser weapons in regard to the power supply and the size of such a weapon. The advantage of the rail gun lies in the higher start velocity achievable (up to 10000m/sec), and therefore it has a nearly straight trajectory which dramatically increases the hit probability. Additionally, the ammunition can be made very small, which would enable a greater amount to be carried on a combat vehicle. Furthermore, the penetration capability is much greater than for conventional guns. Especially the penetration capability is an advantage of the rail gun compared to a laser weapon at long ranges. Furthermore, the survivability of a combat vehicle could be increased when equipped with laser weapons as no explosive devices must be stored onboard.

“A prototype developed by General Atomics Electromagnetics system (GA-EMS) group for the Office of Naval Research has successfully performed initial firings at the Naval Surface Warfare Center in Dahlgren, VA and at the Army Dugway Proving Ground in Utah. The gun is designed to deliver significantly higher muzzle energies than ever demonstrated in a tactical relevant configuration. The full scale ‘Blitzer’ EM Rail Gun System is currently undergoing a series of full energy tests and evaluation by the Navy” (General Atomics & Affiliated Companies, 2012a).

As with the HEL, a use for ground combat vehicles within the next couple of years is not yet being considered as the problems with their size for electric support and the gun itself are not solved. In contrast to the laser systems, rail guns already raise some theoretical considerations related to their implementation in a ground vehicle. For example, BAE pointed out that their new hybrid propulsion system would produce enough electricity to add laser or rail gun weapons to the GCV. Although this statement seems questionable, rail guns will be used in the near future as main weapons onboard U.S. ships. So, even though they are not a realistic option until the next decade, the theoretical implications of such a weapon system will be modeled as an upper bound for main weapon performance (T. Eshel, 2012b; General Atomics & Affiliated Companies, 2012b).

Another issue to be addressed is the addition of secondary weapon systems like a mortar, automatic grenade launchers, or heavy machine guns. The modeled agents already have a variety of secondary weapons. The benefit of such weapons is using the higher firing rates and the greater effect of indirect fire against covered targets. As MANA does not distinguish between cover from indirect or direct fire, the benefits of these weapons cannot be exactly modeled in contrast to direct fire guns. An indirect approach to the issue is to adjust the hit and kill properties for covered targets. As the scenario used in this thesis assumes air superiority for the Blue forces, advanced secondary air defense weapons are not considered, and the absence of enemy air assets would make no difference in the results.

One of the lessons of asymmetric warfare is the need for non-lethal weapons or weapons which are able to destroy certain enemy assets without causing collateral damage. This field is the classical area of *electromagnetic warfare* (EW), which has been mainly used for disturbing an enemy's communication abilities. New technologies like jammers for protection against radio controlled IEDs are just the start of a variety of energy based weapons. Although the field is still wide open for new ideas, there is at least one already under development and field testing: *microwave weapons.* The potential for this kind of weapon is that it has the capability to destroy electronic devices without destroying the environment. Besides this capability, microwave weapons can also cause pain in humans without actually inflicting long-term damage. The aerial deny system of Raytheon or the missiles tests with Counter-electronics High-powered Microwave Advanced Missile Project (CHAMP) of the Air Force are examples of such weapon systems. For the given scenario the traditional effect of EW on communications is modeled, as no other non-lethal weapon is needed. EW defense is also not part of the model.

It is unusual to find *communications and information management* under lethality. The author decided to summarize them under lethality to emphasize the influence of communication and data exchange for fire coordination, targeting information, and allocation, as well as processing this information for the crews of combat systems. New software systems, human factors-oriented design, and advanced data exchange rates increase situational awareness, help to avoid fratricide, accelerate target detection and engagement, and ultimately increase the lethality of the system and the whole deployed force, so that the "combined arms" concept can be utilized (Hudson, 2012; Axe, 2012).

"To date, however, the networks have not been able to provide the necessary information in a complete and timely manner. The existing Blue Force Tracking and Force XXI Battle Command Brigade and Below systems have worked to some extent but are not sufficient to allow complete reliance on them" (Kempinski & Murphy, 2012). With advanced technologies it might be able to achieve the desired effects of superior situational awareness, and so they will be modeled in MANA.

b. Mobility

Speed on Different Surfaces /Acceleration

New kinds of engine systems, especially electric systems, offer new possibilities. *Hydraulic electric propulsion* is advertised as one of the most beneficial new developments for future GCVs, and it is planned to be used by the BAE contractor. Not only the reliability of the drive line system can be increased through the reduction of moving parts; there are also possible alternatives in the location of the engine and the power supply. One advantage for an infantry carrier could be that a "dual sponson engine design clears more space in the fighting compartment, while minimizing the volume under armor, thus saving weight of about three tons. It also enables a two-seat crew compartment, for driver and commander seated side-by side" (Ahearn, 2012). So carrying capacity could increase or more armor protection could be achieved with the same weight as the volume under the armor is reduced.

Hydraulic electric propulsion is said to save 10 to 20 % of fuel for the same vehicle, and much more important it is able to provide the necessary torque immediately so the acceleration of vehicles is faster. As beneficial as these advantages are, the most significant benefit is its design which generates much more electrical energy. Electric energy is considered as a main "bottle neck" for future weapons and protection systems for ground combat vehicles. Last but not least, range and speed could also be increased by this technology as electric propulsion is advertised as more energy efficient and able to produce a higher torque than combustion engines (Ahearn, 2012; T. Eshel, 2012c).

c. Protection/Survivability

The protection or survivability of a ground vehicle is not only dependent on the size and the structure of its armor. Many other factors also contribute to the overall protection of a system. The different layers of protection are shown in Figure 3.

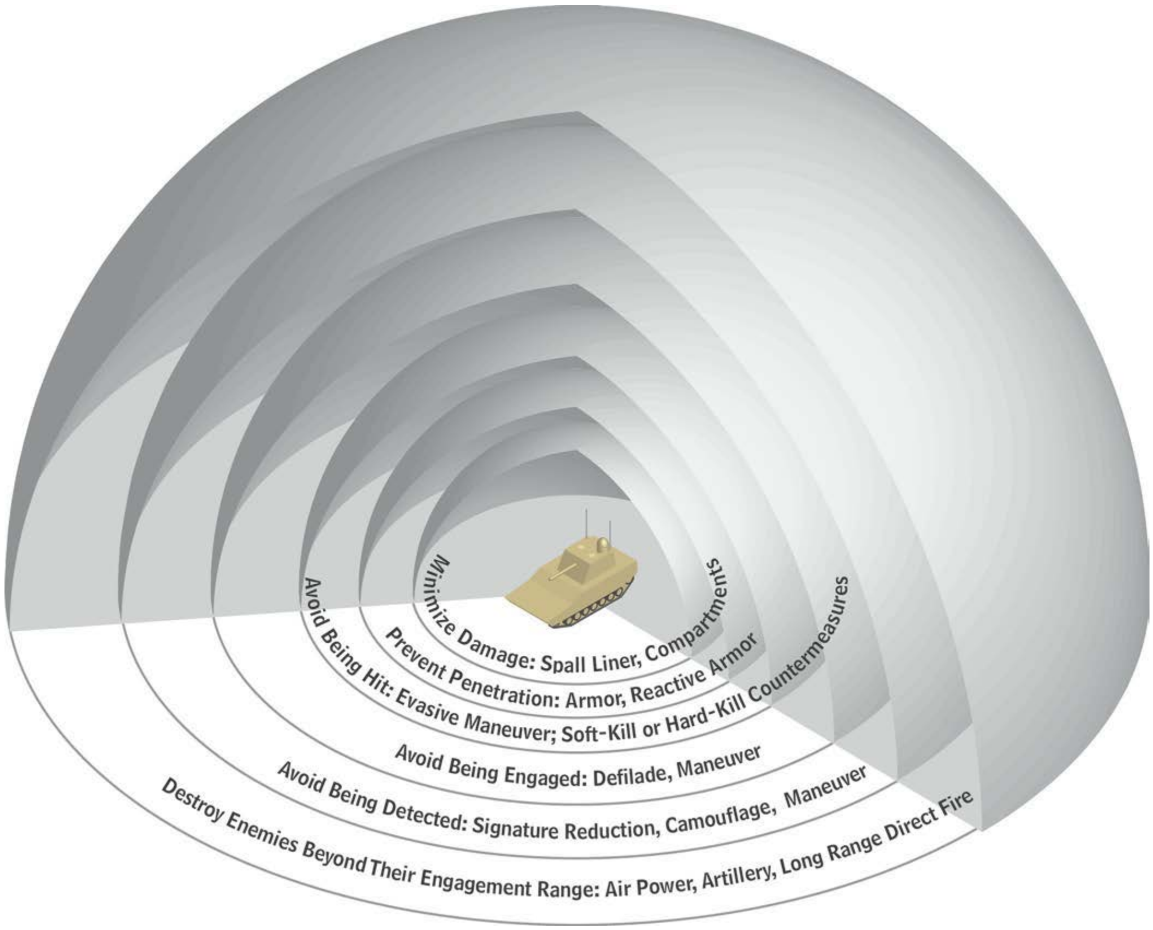

Figure 3. Scheme of the different phases which comprise the protection of a vehicle: "Survivability onion." (From Kempinski & Murphy, 2012)

The first zone shown in Figure 3 is a preemptive kill zone. If long-range systems are able to kill the enemy before it gets within reach this adds up to the increased survivability of the considered vehicle. This can be accomplished by adding a long range, mostly indirect weapon and the corresponding sensor base on the protected GCV or by implementing the force structure with such long-range weapons. The latter is called a "system of systems" consideration and can lead to the examination of the right force mix for a mission. In current deployments the availability of long-range indirect fire support is a tactical consideration. The model takes that fact into account in providing indirect fire through M109 A6 Paladins and adding an organic, indirect fire weapon on the GCV (Rheinmetall Defence, 2013a).

Avoid Being Detected/Concealment

New technologies promise to drastically improve the concealment and stealth capabilities of ground combat systems. The most often used detection sensors in ground combat during day and night time are thermal based as armored vehicles and humans produce a lot of heat. Therefore, there are systems under development to reduce the thermal signature of combat vehicles. An example is the ADAPTIV system of the BAE systems. ADAPTIV works by using lightweight hexagonal pixels which are electrically powered by the base vehicle. "The pixels are individually heated and cooled using commercially available semi-conducting technology"(BAE Systems, 2013).

Once installed the system promises to provide combat vehicles with the following improvements:

- The ability to blend into natural surroundings;
- The ability to mimic natural objects and other vehicles;
- A significantly reduced detection range; and
- Friend – Foe identification

The capability of the ADAPTIV system on thermal sight detection systems is shown in Figure 4.

Figure 4. The picture at left shows a vehicle with no ADAPTIV system; the middle picture shows the effect of the concealment through ADAPTIV; and the right picture shows the capability of the ADAPTIV system for deception as it simulates the signature of a car.

This technology alone cannot provide total cover from detection as there are unresolved issues with heated exhaust gases, noise, dust, or simply detection through normal vision at daytime and light intensifier at night. If only the heat signature can be diminished it already provides huge advantages in detection ranges at night, and there are also new developments to further conceal ground combat vehicles in the other areas. A combination of the ADAPTIV system with an electric engine to reduce the noise and common camouflage seems to be an excellent mix to avoid detection.

Avoid Being Hit: "Soft and Hard Kill" Systems

Another contributor for survivability is ***"hard kill" protection systems***. These systems detect and destroy incoming projectiles of all kinds. One possible system is an HEL weapon. Another major development tree is APS (Active Protection System). For example, the Israeli NAMER infantry carrier is designed to use the integrated Iron Fist Active Protection System currently under development. The different processing steps conducted by a "hard kill" system are shown in Figure 5.

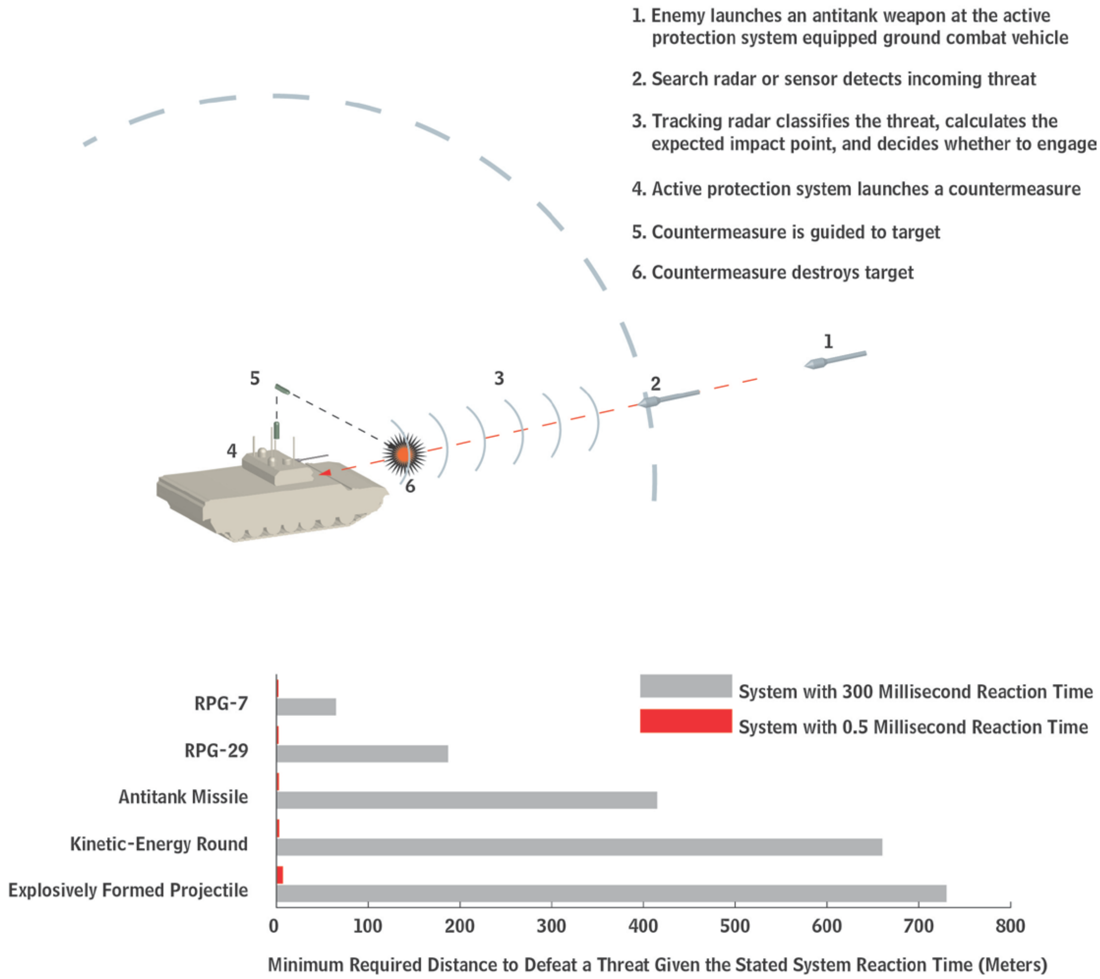

Figure 5. Sequence of events and minimum required distance for a generic hard-kill Active Protection System (From Haug & Wagner, 2013).

The German Rheinmetall Defence Company successfully conducted tests against projectiles fired from ranges fewer than 20 meters, as shown in Figure 6. Their system uses sensors “mounted on the protected platform, to detect potential threats, measure distance and trajectory, providing the fire control system with data for calculation of engagement plans. When a threat is identified as imminent, an explosive projectile interceptor is launched toward it” (Rheinmetall Defence, 2013b). It is likely that future combat vehicles will be equipped with such systems. They are similar to reactive armor, but are more capable and drastically reduce the threat of hitting bystanders. Interaction with each other and similar systems like radar and jammers are still not well known. There is a possibility that they interfere with each other and so decrease the protection effect (Kempinski & Murphy, 2012; Rheinmetall Defence, 2013b; Defense Update, 2009; Pressebox, 2011; General Dynamics Armament and Technical Products, 2013).

Figure 6. German ADS system with incoming missile and ranges for detection (dark grey) and destruction (light grey).

As the effectiveness of such protection systems is difficult to model in MANA, the author chooses to decrease the hit probability of enemy anti-tank weapon systems on the GCVs modeled.

Nearly as important as the “hard kill” are the “soft kill” systems. “Soft kill” systems are designed to prevent incoming missiles from hitting the target without destroying the missile. In this class, there are already a high number of systems operating on modern ground combat vehicles. The most common ones are launchers for fog grenades, which conceal the vehicle from incoming missiles or flare systems and jammers, which are able to mislead advanced intelligence projectiles. Here, a steady progress has been achieved. For example, Rheinmetall developed the Rosy_L–Rapid Obscuring System which is able to conceal even a driving vehicle with sustained fog. As MANA is able to give each system a certain concealment rate, the current concealment of the existing vehicles will be increased in the used DOE (Rheinmetall Defence, 2013c).

Armor

New developments for armor must be examined as it is the most well-known contributor to survivability.

“There are two general classes of armor: passive and reactive. Passive systems work by stopping the projectile through the material properties of the armor components alone. Reactive systems work by inducing an explosion or other response in the armor to reduce the lethality of the projectile by disruption or deflection. Types of passive armor include bulk armor, modular armor, slat armor, and hull shaping. Types of reactive armor include explosive reactive armor and electromagnetic armor” (Kempinski & Murphy, 2012).

For passive armor the use of new materials, especially composite material, decreases the penetration possibilities of existing weapons. For example, CPS Technologies, a producer of advanced Metal Matrix Composites (MMC), is unveiling armor grade materials enabling armor designers to produce ballistic and blast mitigating materials with greater strength at lower specific weights (T. Eshel, 2012d).

The effects of enhanced armor against different kinds of weapons cannot be predicted before extensive tests are conducted, but it is reasonable to assume an improved weight/protection ratio by at least 20%. It must be realized that the use of advanced passive and active armor will increase the cost of a GCV drastically and adding armor can also influence many other performance factors. “Ceramic armor materials can halve the weight per unit of protected area of armor compared with the same metric for steel, but they cost 4 to 12 times as much to achieve that benefit” (Kempinski & Murphy, 2012). Increased costs are the reason why most modern GCV try to implement modular armor packages in their development program to adjust the armor according to the threat environment (T. Eshel, 2012d).

There are additional ways to increase the survivability of the crew and the system. Most of the systems are designed to minimize the damage when the armor is penetrated, while others dealing with a special non ballistic threat and, again, another kind to further enhance lethality or survivability. Some examples are:

- Nuclear, Biological, Chemical (NBC) protection capability
- Fire suppression systems
- Ammunition compartment separated from the crew
- Seats Designed to Absorb Impact of IED/mines
- Remotely controlled turret
- Hunter/killer combat techniques
- Advanced training simulator
- Tactical doctrine
- Evasive maneuver to avoid engagement or to avoid getting hit

There is no question that the items listed are important; all are contents of a balanced system design for combat vehicles and all exist for current combat vehicles. Improvements in these areas will further enhance the mentioned effects and therefore increase the MANA model parameter like firing rate, armor, detection rate and hit probability.

Robotics

The implementation of an autonomous robotic system could influence the current face of the battlefield in many different ways. The possible benefits of such as system include the following:

- Casualty reduction;
- Improved mission effectiveness--robots for reconnaissance, convoy, support, force protection free soldiers for higher-level tasks;
- Improved situational awareness from unmanned air and ground vehicle scouts;
- Seamless integration of manned and unmanned assets into the battle team; and

- Reduced logistics workload, increased focus on mission.

The current systems under development have the potential to totally change the force structure. So could it be possible to use many fewer performing robot systems, instead of fewer higher performing manned systems, to achieve the same goals more efficiently. As the scope of this thesis is to help increase the performance of ground systems in a joint and combined environment this aspect will be left to further studies. The MANA scenario used works with a fixed number of systems and will not be able to determine a tradeoff between numbers and quality (General Dynamics Land Systems, 2013).

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III. MANA V AS COMBAT SIMULATION SOFTWARE

A. WHY MANA V

One important decision of research involving combat simulation is to choose the right simulation software. For this thesis, the author chose Map-Aware Non-Uniform Automata-Vector (MANA-V). MANA-V is a time-step, stochastic modeling environment developed by the Defence Technology Agency (DTA) of New Zealand, and it has been chosen for several reasons.

First, MANA-V is a complex adaptive system intended to mimic real-world factors of combat. It is a low resolution model regarding physical aspects of modeling combat events like shooting, armor penetration, probability of hitting, and so on. Many real-world factors are accumulated into a single value. For example, if a tank is being shot at with a particular weapon the resulting damage depends on the armor thickness at the impact area, the angle the projectile has, the range from which it is fired, the kind of projectile, and so on. MANA simplifies these circumstances in a single range-dependent kill probability. As this can be seen as disadvantageous at first glance, it keeps high transparency in the model. Therefore, MANA is an excellent choice if the purpose of the model is not to get an optimal attack strategy for a certain weapon system, but to look for the most influential factors or interactions on defined MOEs, which is the case in this thesis. Another advantage resulting from the low resolution is that it allows running multiple replications due to lower computational times and therefore enables the analyst to use design of experiment and data farming techniques in an effective way (McIntosh, 2007).

Second, MANA is an agent-based simulation, which allows the agents to react on their own sensor inputs. It is not necessary to prescript the behavior of the agents which allows for a great variance in outcomes comparable to real human behavior. This enables the analyst to find and study unlikely outcomes and draw conclusions from these outcomes. To do this, the seed which represents the random values used by the software, has to be stored, and an interesting run can then be repeated by the analyst. The author found that the seed for the command line runs on the cluster computer used was not identical to the seed used at the graphical user interface (GUI). Thanks to the advice of Ms. Mary McDonald and Mr. McIntosh of the New Zealand developer team this "bug" could be fixed during the study.

A third advantage of MANA is that it provides an easy-to-use GUI and has a rapid learning curve in modeling agents and building a scenario. The graphical representation of the battle allows the analyst close control of the agent behavior, high transparency of cause and reaction, and fast changes of input parameters.

Furthermore, MANA is capable of data farming, which means that it enables the use of high dimensional design of experiments. It is possible to create a certain design of ranges for input parameter and run them with a specified number of replications. It is even possible to automatically run different replications with a certain parameter (for example, a weapon system) enabled or disabled. As variance is brought in by the agent's behavior and random events it is an inherited part of the output. Therefore, it is not only possible to look for an optimal solution, but also to find a robust one. This is essential as every combat simulation, regardless how detailed it is, is not a replica of reality and is logically error prone.

In sum, MANA is exactly the software an analyst needs to get quick insights and find out major influential factors and dependencies as it focuses on main details. For exact numbers or detailed answers a more physically based model or real-world experiments are more applicable.

For a detailed exploration of the capabilities of the MANA-V software the author refers readers to the MANA 4 and MANA V user manuals (McIntosh, 2007; McIntosh, 2009).

B. DRAWBACKS

As stated before, MANA is a low-resolution model and has several disadvantages. The ones which influence the purpose of the thesis must be mentioned and are stated in the following paragraphs.

Sensors

MANA uses two types of sensors: simple sensors and advanced. The simple sensor is a “cookie cutter” sensor for which the user can specify one detection range and one classification range as well as a sensor aperture in degrees. The advanced sensor has the same features, but it allows also for probabilistic detection rates and probabilities of classification. Therefore, the user can model a realistic detection behavior within the advanced mode.

Ground combat vehicles usually have magnifying sensors for their main weapons, which limit the field-of-view to small segments. These sensors are then moved in a tactical assigned direction to scan larger areas. For example, each Abrams tank in a platoon is assigned a 60 degree angle to scan with the main thermal sight (10 degree aperture) when the platoon is moving (Figure 7). MANA is theoretically able to simulate this behavior as it has the option to give agents a facing direction and to assign a slew rate in a sector. Unfortunately, this feature does not work as well when enemy targets get very close.

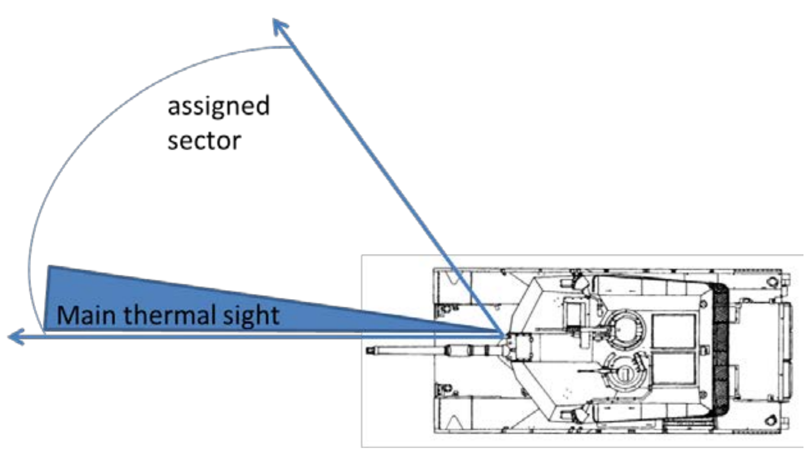

Figure 7. Field-of-view for an Abrams tank thermal sight.

In reality, it is one of the greatest weaknesses of armored vehicles that they have dead spots in their proximity—especially in urban combat. In MANA the problem is even worse as simulation tests showed that the vehicle agents are unable to react realistically in close combat, and they drive by enemies at close ranges without facing the sensors in the enemy's direction. Agents are unable to detect enemies even when they see them at longer distances.

To create a more realistic behavior the author chose to use 360 degree sensors and adjusted the detection rate. For very close enemies, vehicles get a "cookie cutter" sensor with 360 degrees to simulate the possibility of crew members looking out of the vehicle hatches. In reality this is not always possible, especially if the vehicle is under attack.

Armor

The setting for armor in MANA version 5.0 is not detailed enough. When an armored vehicle is hit, the probability of getting damaged or destroyed depends on the ability of the projectile to penetrate the armor at the impact location. Whether penetration takes place depends on various factors such as the shooter's distance from the target, angle of impact, the target's armor thickness and angle of attack on the impact location, and finally the penetration ability of the projectile against the special armor class of the target. To make it more complicated many modern ground vehicles also have a variety of active defense systems like a smoke grenade discharger or flares. These kinds of systems are also only effective against one class of projectile, such as flares against heat seeking missiles.

In MANA it was only possible to set a single penetration value for a weapon and a single armor thickness to an agent. This means that an anti-tank missile with an average penetration capability of 999 mm RHA (= rolled homogeneous armor equivalent) has no chance of penetrating a 1000mm RHA armored tank. High resolution combat simulation divides vehicles in different zones with different armor thickness, calculates the probability of hitting a zone, and then calculates the probability of penetrating the armor in the zone given a hit and taking all other parameters into consideration. Even when the armor is penetrated, there are different possibilities of damage results.

For the purpose of the thesis it was sufficient to combine these factors and approximate the penetration capability of the weapon by a normal distribution with a user chosen mean and deviation to achieve the desired resolution. Changes in the MANA software were done by the New Zealand developer team according to the recommendations of the author.

C. SUMMARY

MANA has the ability to model realistic behavior and has proven to possess the tools for approximating physical effects of high resolution software through indirect means. This leads to quick insights and covers relationships between battle influential factors. As MANA is designed for this purpose, it only adds necessary physical details. It will be necessary to use a higher resolution model for approximating the specifications of a special ground combat vehicle sufficiently close after the results of the MANA model, and first field tests show the basic relationships.

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IV. SCENARIO

The modeled scenario is discussed in this chapter. First, it is explained why the model fits the purpose of the study and then how it is modeled. Finally, the discussion covers what could not be addressed due to software restrictions.

A. SELECTION CRITERIA

Currently, military doctrine divides the deployment environment in peacekeeping operations (low battle intensity), irregular combat (asymmetric warfare), and conventional combat (major conflict between militarily developed states). For a specification scenario it is important to contain the predominant types of threat for GCVs in these deployment types. These types are according to Kempinski & Murphy (2012):

- Small weapons and unguided mortars for peacekeeping;
- Rocket-propelled grenades, improvised explosive devices, explosively formed projectiles, and unguided mortars for irregular warfare; and,
- Tank rounds and large antitank weapons in conventional combat.

For this thesis, the scenario selection is based on following additional considerations:

- It must be a realistic battlefield environment, which can be used for the full spectrum of warfare.
- It must contain the most advanced major ground vehicles in use and also the most likely joint combat-arm systems.
- The terrain must be challenging for ground combat vehicles and allow short to long range combat situations.
- It must be applicable for use at a reinforced company level to keep the runtime for MANA at a reasonable magnitude.
- The scenario should be designed to inflict heavy damage, including mission failure, on the BLUE forces. This is a prerequisite to see the improvement the new system can achieve.
- The scenario should have been widely used, should be officially approved and should be tested with other combat simulation

software or war gaming to achieve a higher level of confidence in the results.

- The force structure must address the requirement of containing the most likely mix of combat systems according to actual doctrine. This is important, as the force mixture can strengthen or diminish the relationships between the factors of interest. For example, if someone tests only battle tanks against battle tanks and he would examine the effect of giving one side superior range this would lead to a significant advantage for this side. If both sides have long range indirect fire systems available, the casualty rate of the upgraded side would increase even when the tank ranges are adjusted as in the first case. Therefore, the scenario should contain the most likely force structure to capture the effects of the corresponding interactions.

The chosen scenario framework is taken from a division level U.S. Army Training and Doctrine Command (TRADOC) scenario called MLS1 (Brown et al., 2009). This scenario contains the attack of a reinforced mechanized infantry company of the 7/HBCT (heavy brigade combat team) against parts of a mechanized battalion based on a fictive scenario taking place in the state of Colorado. A tactical overview of the scenario is shown in Figure 8.

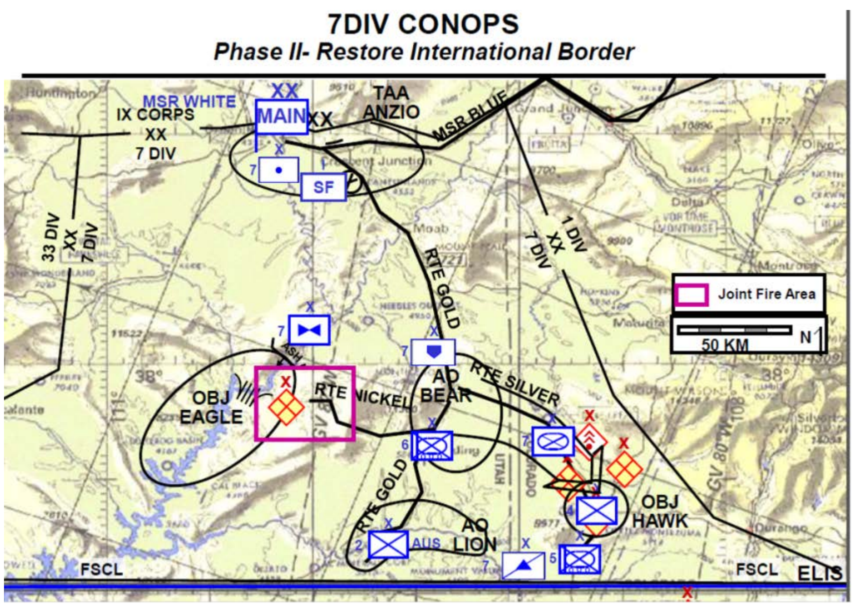

Figure 8. Division level CONOPS of the chosen TRADOC scenario.

The U.S. forces are equipped with Bradley A3 infantry vehicles and supported by Abrams M1A2 Sep battle tanks. All BLUE combat support units are taken from the scenario description.

The Bradley Company and the enemy provide only a basic scenario used as a reference. The real purpose of the simulation is to analyze the influence of a new ground fighting vehicle on the defined measurement of performances in comparison to the existing systems. Main measurements of performance are the following:

- MOE1: Own casualties
- MOE2: Enemy casualties
- MOE3: Time for reaching the mission objective
- MOE4: Casualty ratio = $\frac{RED\ agents\ killed}{BLUE\ agents\ killed}$
- MOE 5: If Bradleys are substituted with future GCV,
  GCV destroyed **and** BLUE infantry lost
- MOE 6: If M1 Abrams are substituted with future GCV,
  only GCV destroyed
- MOE 7: BLUE victories (conditions defined in Chapter V)

Notice that for an infantry carrier the number of infantry killed is an important MOE as infantry losses can occur while the infantry is mounted or dismounted. In the mounted case it is the task of the carrier to protect the infantry as they are not able to fight. In the dismounted case the carrier has to provide additional firepower for its dismounted squad. So in both cases the performance of the carrier directly influences the casualty rate of the infantry, and therefore it is a valid MOE for the carrier.

To achieve tactical insights, the properties of the BLUE agents' modeled weapon systems and their behavior should be as realistic as possible. The following section lists the modeled systems and some of the detailed modeling considerations. Other **physical properties** like ranges, used weapons, sensors, equipment and their references are available in electronic format at the NPS SEED Center (for more information, contact Professor Thomas Lucas). The used sources for the set values are the TRADOC scenario itself, the Global Security data base, the Information Handling Services (IHS) Jane's catalog, the Federation of American Scientists homepage, official field manuals and doctrine papers, and, if no other source was available, Wikipedia.

B. PHYSICAL PROPERTIES FOR BLUE AGENTS

1. Bradley M2A3

The main ground combat vehicle for the scenario is the Bradley M2A3. The Bradley is an infantry carrying ground combat vehicle with a crew of three and is capable of transporting up to seven additional infantry soldiers. As MANA is only capable of specifying one value for average armor thickness per agent, the author chooses a value according to his military knowledge. An infantry carrier offers good protection against small and medium arms, but is usually penetrated by anti-tank missiles and main battle tank cannons. The sensor settings for the Bradley are according to the basic considerations in Chapter III. So, it is possible for the Bradley crew to look out of the hatches and detect enemy agents at close distances at 360 degrees. These settings must be adjusted if urban combat is modeled with the Bradley agent.

Logistical considerations of ammunition and fuel are modeled, but due to the duration and intensity of the battle have little influence. All Bradleys have a 100 % reliable communication link from and to the company headquarters.

2. Bradley Infantry Squad

For simplicity and computational run time the seven infantry agents in a Bradley are modeled uniformly. This means all infantry agents are able to use all squad weapons with a reduced fire rate. The ammunition is available for all agents in the infantry squad. For example, if there are five M4 with 250 rounds each in the squad, the ammunition of the squad is 5 x 250 = 1250. If one infantry agent is killed, the squad loses 1/7 of its firepower. This aggregation does not affect the basic relationships this thesis is designed to discover.

As infantry is able to conceal itself much better than vehicles, the agents have a terrain independent concealment factor. This factor is lowered when the infantry use their weapons.

The infantry communication links are only established with their corresponding infantry carrier. They are unable to reach the company headquarters directly.

As mechanized infantry is usually deployed within the "combined arms concept," the BLUE forces have access to the following assets.

3. Abrams M1A2 SEP

The most common support weapon systems for mechanized infantry are main battle tanks, as they provide the necessary superior firepower and follow similar doctrines. In the given scenario, the heavy tank component is represented by Abrams M1A2 SEP tanks. This is the latest upgrade of the Abrams tank versions. As it is also possible that a future ground combat vehicle will be developed as a battle tank-like system, and the German army plans to start an acquisition project of a new major battle tank system (Reuters, 2012), the thesis will also focus on analyzing this kind of vehicle.

The armor of the Abrams tank represents state-of-the-art protection in the front area, but the Bradley has different values for the roof or mine protection. The Abrams is also equipped with active protection such as a smoke grenade launcher or radar warning systems. MANA combines these to a normal distribution with a mean and a standard deviation. As before, the author chose to adjust for this fact according to his own military experience and the found specified hardware values. The MANA values are set to represent the fact that the Abrams tank has a good survivability against most anti-tank systems and is normally not penetrated by older battle tank systems or small arms fire.

The armor penetration capability of the 120 mm main gun is heavily dependent on the range between target and gun, but due to restrictions of the

MANA software the lower penetration at long ranges can only be taken into calculations by a lower hit probability at these ranges.

The sensor considerations are exact the same as those noted in Chapter III or for the Bradley vehicles.

Logistical considerations of ammunition and fuel are modeled, but due to the duration and intensity of the battle have little influence. The Abrams have a 100 % reliable communication link from and to the company headquarters.

4. DQ 11 RAVEN UAV

The RAVEN UAV is a shoulder launched reconnaissance UAV, which is capable of detecting personnel and vehicles and sending the information in real-time to a command post. The detection probability depends on many factors like weather, concealment, type of target, daytime, equipped sensors, and flight attitude. In the given scenario, the sensor of the UAV distinguishes between vehicles and infantry targets with different effectiveness.

The RAVEN in the scenario is controlled by battalion headquarters. Therefore, the information has a delay of five minutes to reach the company commander. The endurance is set to 90 minutes before the RAVEN returns to refuel. The ground unit of the RAVEN is not moving during the whole scenario so the UAV's "time over target" will decrease over time due to fewer times over target. Indirect fire support becomes available, if the RAVEN spots enemy troop concentration with a delay of 10 minutes. If the RAVEN spots an enemy it stays at the enemy position until it loses contact or refill is necessary. To decrease the probability of the RAVEN being shot down—as it unrealistically flies exactly to the enemy position and therefore in the enemy effective combat range—its concealment rate is set to nearly invisible. The UAV has a communication link to the Battalion HQ which is 100% reliable. The modeled UAV has a 360 degree view. The (in reality) restricted field-of-view for the UAV is taken into consideration by adjusting the detection rate.

5. Close Air Support through APACHE 64D Attack Helicopters

The BLUE forces have the support of two Apache attack helicopters in a covering force role. The Apache attack helicopter has a number of countermeasures and is very maneuverable which makes it hard to kill, and the helicopter has proven to be very resistant against enemy fire—especially small arms—even without armor. As it is not possible to model these physical properties directly in MANA, an "Apache" can take two hits before it is shot down. The Apaches have an endurance of two hours. After returning to a Forward Arming and Refueling Point (FARP) they are rearmed and refueled, but they are not repaired. An undamaged Apache returns to battle after 20 minutes in the FARP. Empty weapons reload automatically within 40 minutes. Damaged helicopters immediately return to base. After 30 minutes the damaged Apache becomes available again, but the next hit kills it. The modeled behavior is to attack the enemy at long-range distances, if they detect them and stay out of the reach of small arms fire. The Apaches always follow the ground forces or fly before them as reconnaissance unless they get enemy target information by their own sensors or via communication link. Then, they engage the nearest targets detected, including scouting out unknown detections.

6. Indirect Fire Support from 155 mm Howitzer

Indirect fire in the scenario can be requested by the troops on the ground, can be triggered by UAV information or by other reconnaissance means (see below). The fire request is executed whenever a threat threshold of 10 is exceeded. This means that the howitzer—like real artillery—do not open fire on single targets like an infantry man, but only on high value targets and groups of detected enemies. The amount of fire for the company is limited to four rounds per minute for three minutes with a break of 20 minutes between the next salvos. The howitzer fire support is represented by one stationary agent. The howitzer has unlimited ammunition. It is possible that the indirect fire kills its own troops as there is a three- to five-minute delay in the targeting information depending on the target information source.

7. Indirect Information

Normally, a lot of information is provided by higher headquarters before and while an attack is executed. The source of this information can be a satellite, human intelligence, or signal intelligence. To model this effect, the company headquarters agent detects enemies at a low rate on the whole battlefield and provides this information to the BLUE agents. As the information of higher headquarters must normally be confirmed by other forces, the information is provided nearly exclusively as unknowns who lead to attraction from BLUE air assets which then do reconnaissance and classification of the enemy.

C. PHYSICAL PROPERTIES FOR RED AGENTS

The RED agents are based on the enemy given in the TRADOC scenario, but are adjusted to use the most modern versions of the given systems. The main reason for the adjustment is to test any future system against the most sophisticated enemy known and not against systems which will be no longer be in use when the GCV is deployed. Another reason for the RED force upgrade is that RED is supposed to inflict heavy casualties on the given BLUE force. This is necessary to measure the improvements of the new systems.

1. RED Infantry

The major “system” of the RED force is the infantry squad, as the TRADOC scenario uses an infantry battalion as the RED force. The author makes the assumption that the enemy infantry has equal qualities according to training, motivation, command and control, as well as leadership skill as do the BLUE forces. Only the weapons are different. These infantry squads are equipped with the most advanced weapons from possible “hostile” states. For example, each squad has 2xRPG-29 anti-tank grenade launchers.

These infantry squads have also special heavy weapon teams attached. As additional long-range anti-tank capability they have MILAN anti-tank missiles. For augmented indirect support against infantry enemies RED has 60 mm mortars and AGS-30 weapons (heavy grenade launcher) attached.

2. T90M Tanks

The T-90M tanks are modeled to have the most sophisticated enemy tank system available. They are not part of the TRADOC scenario, but engaging with them allows a good measurement of performance for a future ground combat system.

Lacking exact data about weapon accuracy and armor for the T90M tanks, the author assumed the same qualities as those of the Abrams M1A2 SEP. Additionally, the T-90M is equipped with many active protection measures like jammer, radar alert, dazzle paintings, etc. Therefore, they are modeled with a concealment rate of 0.2.

The armor penetration capability of the 125 mm main gun is heavily dependent on the range between target and gun, but this can only be taken into calculations by a lower hit probability. The T-90M has REFLEKS M/AT-11 anti-tank missiles as an additional main weapon system which gives it a superior range against the BLUE ground forces. The sensor systems apply the same considerations, as stated in Chapter III.

3. SA-18 SAM (Surface to Air Missile)

With assumed BLUE air superiority, it is likely that RED uses man-portable air defense systems (MANPADs) to shoot down BLUE aircraft as they can hide easily in a mountainous area. The TRADOC scenario contains this kind of weapon for the RED forces, but the author chose to upgrade them to the SA-18. The SA-18 is a modern surface to air missile (SAM) similar to most of the SA family weapon systems and has the ability to shoot down even modern fighter jets.

4. 120 mm Mortar

In the scenario, the 120 mm mortar is used as the main indirect fire support for the RED side. The mortar modeled has unlimited ammunition and a reload rate of 10 min. The mortar depends on fire requests from other units and has no known sensors. It is possible that the 120 mm mortar causes fratricide.

5. Antitank Mine TM 83/IED

As IEDs are one of the most lethal and common weapons in asymmetric warfare they must be taken into consideration. For symmetric warfare the same applies to antitank mines as they are comparably cheap and available in high numbers. Mines and IEDs have a high concealment capability depending on the operator skills. In the given scenario the concealment is modeled as the highest rate before becoming totally invisible, which represents a very skillful mining.

The mine/IED agents used in the scenario represents not only antitank mines, but also anti-personnel mines to prohibit removal by infantry. Therefore, they have a simple sensor with a radius of 100 meters for mines and 50 meters for IEDs. After a mine/IED is activated or detected, the position of the minefield/IED is known by BLUE, and it can be avoided. To model the effect that the minefield/IED has become useless or even cleared, the mine/IED can be attacked by BLUE agents and is removed in this way. If the mine/IED explodes, the agent disables itself after one shot. As destroyed mines/IEDs do not count as casualties, they conceal themselves after shooting.

Most modern ground combat vehicles have relatively effective mine protection. The problem is that it is much easier for the attacker to increase the penetration strength of the mine/IED than it is for the defender to increase his protection. In the modeled scenario the mines are designed for taking out the most armored vehicles of BLUE (Abrams tanks) with a 50% change. So, if a less protected agent is hit by a mine, it is usually killed.

6. RED Communication

The RED force command and control structure is different in the three modeled battle phases. This is explained in detail later in this chapter (see “Battle Modeling”).

D. AGENT BEHAVIOR

The most important agents–infantry, main battle tanks, Bradleys—have the following states (which equals their behavior) modeled:

1. Infantry

Infantry soldiers, including those carrying heavy weapons like anti-tank missiles, have the following states modeled:

“Default:” RED infantry starts with a very high concealment factor corresponding to the fact that they have prepared and camouflaged positions. BLUE infantry has a lower concealment, but as they take cover immediately when they dismount the value is still high compared to a vehicle.

“Taken shot at:” Whenever infantry is *shooting* they can be detected more easily and their position can be located. To model this fact the concealment is reduced after the infantry opens fire.

“Shot at:” Whenever infantry gets shot at it takes cover. Therefore, their concealment is modeled very high which corresponds to a low probability of getting hit. When the infantry has taken cover, it is not able to use its weapons. This represents the effect of “*suppression.”*

“Reached alternative waypoint:” Whenever BLUE infantry is dismounted and its carrier is destroyed, the BLUE infantry will try to get to the final waypoint on its own.

2. Main Battle Tanks

“Default:” BLUE tanks will follow their waypoints if no enemy is detected, but will also stay close to the Bradley to protect them. RED tanks do not move at all before the BLUE forces reach a minefield, but then they start a counterattack, which represents their mission as the RED reserve force.

“Enemy contact:” If BLUE or RED tanks detect enemies themselves or get the information via radio, they will go into engagement mode which means they move with a slow rate toward the enemy and take cover. Tanks will stay at a certain distance from the enemy and use their main guns as they are not designed for close combat.

3. Bradleys

“Default:” Infantry carriers will follow their waypoints with the infantry mounted. If enemies are detected a Bradley will stay on the route, or when the detection is close, engage the enemy.

“Shot at:” As soon as the enemy opens fire at a Bradley it dismounts the infantry and provides cover fire for its infantry squad. In reality, this might not always be the case, but the agents cannot distinguish between fire that endangers the vehicle and fire that could penetrate the armor.

“De-embussed Children:” When the enemy is destroyed or no longer detected, the Bradley agents will search for additional enemies. After 30 minutes, they mount their infantry again and proceed with the mission.

4. Agent Summary

After many tests with different force levels, the author chose to use following agents shown in Tables 1and 2 to achieve the desired effect of about 30 to 50% BLUE loses which leads to some RED victories.

Table 1. Overview of BLUE Forces: modeled types of forces, number of MANA agents of each type, and represented manpower.

Reinforced 2nd Comp 1/28 Mech Inf Bat; 7./HBCT; 7./ArmyDiv (Department of the Army, 1998)			
Type	**Total Men**	**Men per Agent**	**MANA Agents**
4 x Bradley M2A3	12	3	4
4 x Bradley infantry	28	1	28
Platoon Abrams SEP M1A2	16	4	4
2 x AH64-D attack helicopter	4	2	2
M109A6	4	4	1
RQ11 RAVEN UAV	0	0	1
BLUE_Company_HQ	0	0	1
sum	**64**		**41**

Table 2. Overview of RED Forces

Parts of reinforced Mech Inf Btl			
Type	**Total men**	**Men per agent**	**MANA agents**
3 x infantry squad	48	1	48
Platoon T 90 tanks	16	4	4
Mines/IED	0	0	6
SAM-18	2	1	2
Mrs 60 mm	3	1	3
Mrs 2S12 120 mm	5	5	1
AGS 30	4	1	4
3 x MILAN	6	1	6
RED_Company_HQ	0	0	1
sum	**84**		**75**

E. BATTLEFIELD FACTORS

As important as physical properties of agents are, the "other battlefield factors" are most influential for explaining historical battle outcomes.

1. Battlefield Factors Not Used in the Scenario

Both time of day and weather are major contributors to the performance of weapons systems. For example, a superior night vision of a weapon system could give one side a decisive advantage that would not be the case during daytime.

Weather has also proven to be a decisive factor as it affects many physical properties of weapon systems and soldiers in terms of detection ranges, movement rates, orientation capability or the availability of air assets. Therefore, the influence of both factors should be considered in the specification process, but both factors are not readily available in MANA. To avoid any inconsistences in the analysis the scenario is chosen so that these factors do not alter the results. The author makes the decision to adjust the enemy forces to have similar properties to those of the BLUE agents. So, weather and daytime will not give one side an advantage.

Nevertheless, the missing battlefield factors must be kept in mind for the analysis part of this thesis to draw the appropriate conclusions and find accurate relationships between the factors.

Even if the author is confident that the major relationships can be found with the current version of MANA—as has been proven in many other theses done with MANA before—it must be stated that any interactions of the considered battlefield factors with these two factors are lost and must be left to future research.

2. Battlefield Factors Considered

The considered main battlefield factors, and how they are implemented in MANA, are described in the following sections. A brief summary of all other considered factors is given at the end of this chapter to provide the reader with a better insight into the simulation capabilities.

3. Impact of Terrain and Evaluation on Line of Sight

MANA is able to calculate the line of sight (LOS) corresponding to the evaluation and the terrain. Every agent has a certain height for its sensors, and this value is used to determine the area they can see. Terrain can cut the line of sight and is modeled in MANA with three properties:

- “Going” adjusts the given physical movement rate ground units have and so determines the speed in a given terrain.
- “Concealment” determines how well agents can hide in it.
- “Cover” stands for the protection the terrain offers against all kinds of weapons.

4. Situational Awareness and Behavior

Every agent in MANA has its own situational awareness map. This map contains information from its own sensors and from other agents transmitted through the established communication channels. Every agent in MANA reacts to its available information and not the “real,” simulated situation corresponding to a certain set of behavior rules. This is most important as it enables every agent to create realistic battle behavior and allows analyzing the effect of individual situational awareness.

5. Different Agent Classes and Threat Levels

MANA has the capability to assign agents a certain class and a certain threat level. In the scenario agent classes are used to differentiate between infantry and vehicles for sensor detection and classification ranges, as infantry is harder to detect than a vehicle. The agent class is also used for defining which weapon shall be used against which target.

The agent class is also used to establish a tactical fighting systematic. For example, it enables the agent to shoot at the most dangerous enemy first and to avoid unrealistic firing behavior like hitting a battle tank with an AK 74 rifle. The threat levels are used to prohibit tactical wrong decisions like shooting at a single infantry soldier with heavy artillery.

Table 3. Different threat levels and classes for MANA agents are used to enable distinction between the agents.

	Threat Levels	**Agent Class**
Non-lethal	1	1
Infantry	1	2
Infantry Carrier	3	3
Battle Tank	4	4
Rotary Wing	5	5
Mine/IED	1	6

Other factors implemented in the scenario include the following:

- Sensor capacities
- Sensor field-of-view
- Direction of sensors
- Sensor height
- Weapon ranges
- Weapon effects
- Possibility of fratricide
- Communication (ranges, delay of information)
- Armor
- Rate of fire
- Reaction time
- Ammunition
- Fuel
- Weapon angels

- Personal Concealment
- Cover due terrain and prepared positions
- Changed behaviors for agents shoot at, injured or enemy in sight
- Platoon formations
- Aggregated higher command intelligent sources
- Given orders

F. DETAILED SCENARIO DESCRIPTION

Several elements of the scenario, including the terrain and tactical considerations, are discussed in detail in this section.

1. Terrain Description

The battlefield (Figure 9) is a box measuring 30 km in width and 40 km in length taken from Google Earth. The area represents terrain on the western border of the state of Colorado in the United States along the Highway 491.

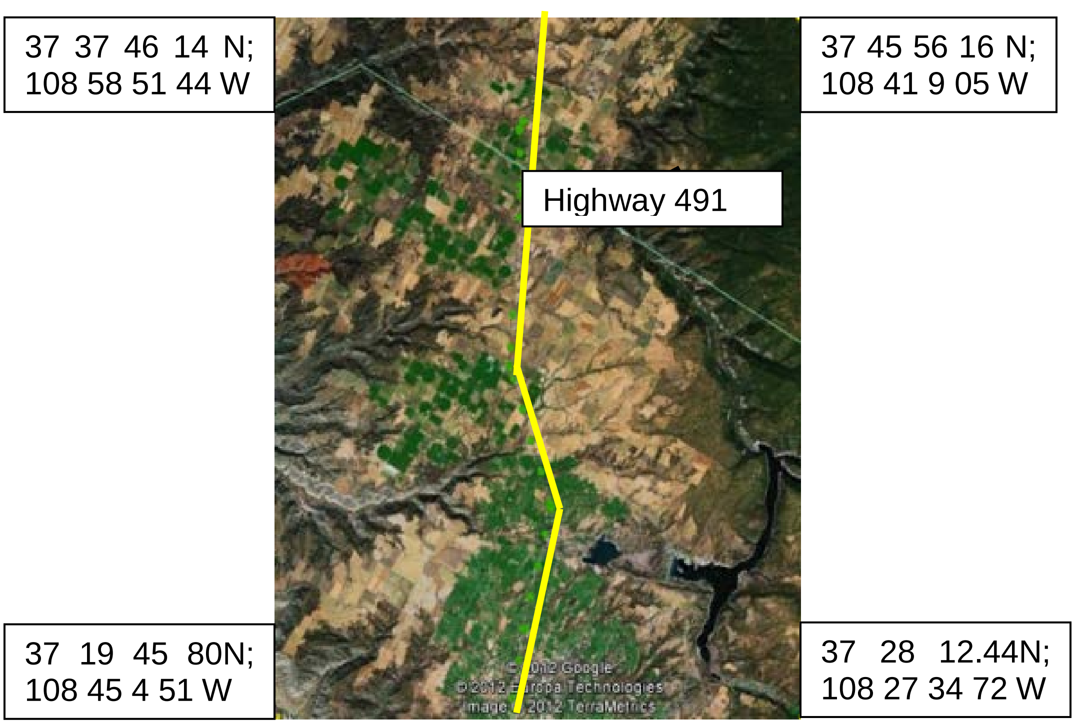

Figure 9. Battlefield map (From Google Earth, n.d.).

The scenario terrain is chosen to provide a challenging battlefield with good cover possibilities for the infantry, but also to allow for areas where long range, air based and high technology weapons can be effectively applied.

The terrain consists of different layers. The basic layer is called “Typical Terrain” and represents the prevailing terrain type in the area which provides a high movement rate for combat vehicles but also some cover and locations for battle positions. Especially for infantry, this terrain provides good possibilities for concealment. Figures 10 and 11 are pictures made from the area.

Figure 10. Picture of the “Typical Terrain.”

In the west of the chosen area the terrain consists mainly of rocky canyons. These canyons are only accessible by vehicles on a limited basis and provide excellent cover and concealment. Therefore, it is utilized by the RED infantry forces to increase their combat strength.

Figure 11. Picture of the “Canyon Rocks.”

As the canyons are like cuts in the terrain, the line of sight calculations are especially important in these areas. Highway 491 provides mechanized forces the ability to move at high speed from north to south. The forests in the south of the operation area are modeled as dense vegetation with high concealment and medium cover. Sensor detection rates are very restricted for agents in this terrain. The river in the east prohibits the moving of all ground units further to the east.

MANA settings for the used terrain types are given in Table 4.

Table 4. The values used for terrain calculations (how fast an agent can move, how easily it can be hit, and how likely a detection for a given sensor is).

Type	Going	Cover	Conceal
Billiard	1	0	0
Wall	0	1	1
Hilltop	0.9	0.1	0.95
Road	1	0	0
LightBush	0.75	0.1	0.3
DenseBush	0.2	0.3	0.9
Water	0	0	0
TypicalTerrain	0.8	0.3	0.6
CanyonRocks	0.1	0.6	0.9
Forest	0.4	0.2	0.7

The terrain has been modeled in MANA (Figure 12) where every terrain type from Table 4 is represented by a certain color.

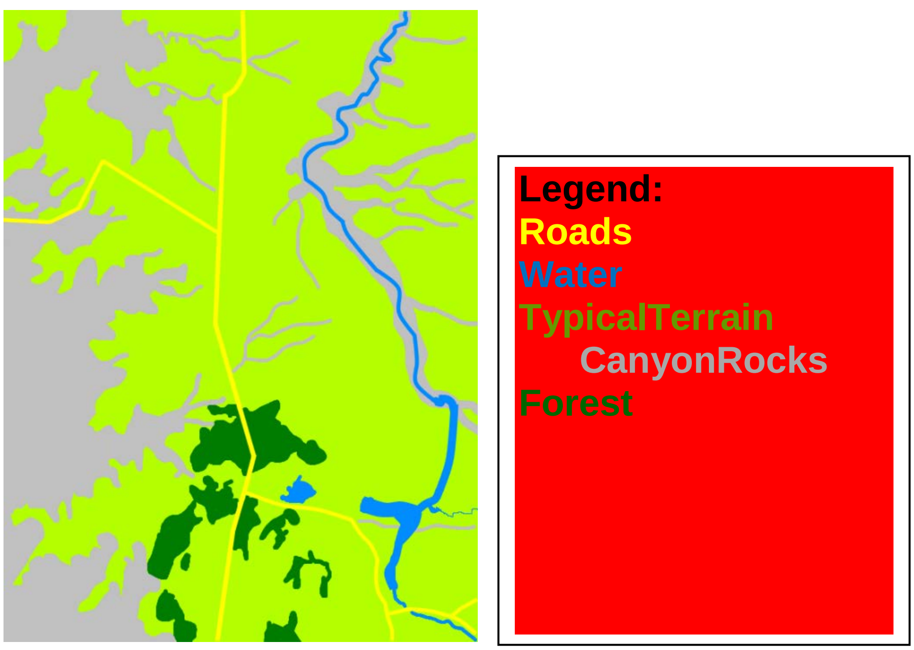

Figure 12. Map of terrain types modeled in MANA.

2. Tactical Description: BLUE Force Mission

Reinforced 2nd Company 1/28 Mechanized Infantry Battalion attacks along Highway 491 30 km to the south and takes Object 1 as a prerequisite for the future attack of the battalion against Object HAWK. The 2^{nd} Company is the major effort and is reinforced by a platoon of M1 Abrams. It has priority in indirect fire support and is the main focus of the battalion's UAV reconnaissance effort. The Apache attack helicopter of the 2/MAW (Marine Air Wing) will provide close air support and additional reconnaissance capabilities. The intent of Commander 2^{nd} Company is to maintain as much attack speed as possible to keep the enemy off balance but also to destroy detected enemies in the area of operations. After reaching Object 1, 2^{nd} Company will secure the object until follow-on forces of the 3^{rd} Company attack over their own positions for Object HAWK. The 2^{nd} company will then follow. The operational plan is sketched out in Figure 13.

Figure 13. Graphical operation plan of BLUE forces.

3. Tactical Description: RED Force Mission

As shown in Figure 14, the operational plan of the RED forces consists of three phases that are carried out by three infantry groups.

The mission of Infantry Group 1 is to attack the BLUE forces from fortified and concealed positions at close range with surprising fire and cause as many casualties as possible in order to break the BLUE attack speed.

At the identified ambush site, they are to attack the BLUE armored vehicles at long ranges with flanking fire from fortified and concealed positions to cause casualties.

Meanwhile, Infantry Groups 2 and 3 use mines and IEDs to fortify the northern position. When the BLUE force reaches the minefield, attack it with Infantry Group 2 and indirect fire support from the 120 mm mortar. The T90-M platoon will counterattack and destroy BLUE forces at the minefield. The SA 18 SAM team provides air defense. Infantry Group 3 will intercept any BLUE force that breaks through the northern position. Company HQ will coordinate fire requests and provide enemy information. All forces will fight from prepared defense positions and will use the advantage of surprise. The intention is to inflict as many casualties as possible and defend successfully against attacking BLUE forces.

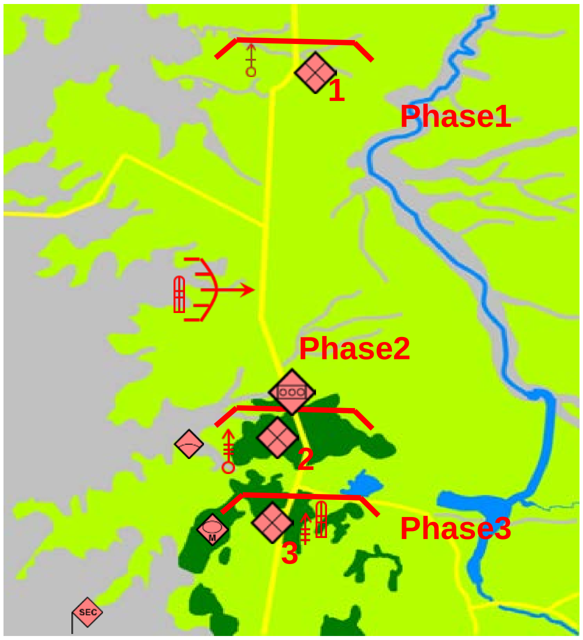

Figure 14. RED three-phase operational plan.

G. BATTLE MODELING

The battle itself is divided in three phases according to the RED defense plan. The author chose this approach to achieve different fighting situations in the full spectrum of war in one scenario. As in reality the outcome of one phase influences the other phases.

1. Phase 1: Ambush

The first phase represents an ambush which can take place in irregular warfare and peace support operations. The enemy (Infantry Group 1) does not have the fire power necessary to defeat the BLUE forces. Its aim is more to inflict casualties on BLUE. Therefore, the RED infantry tries to let BLUE get close and then attacks with small arms fire, heavy machine guns, RPG 29 and 60 mm mortars. After RED opens fire, the superior fire power of BLUE usually destroys RED. BLUE has the advantage of immediate support by UAV, CAS, and 155mm indirect fire. Sometimes RED is already detected by BLUE before BLUE is in the killing zone, which usually leads to a “zero-casualty” victory of BLUE in this phase.

a. Unrealistic Behavior

Normally ambushers do not attack an enemy force of such a superior strength without providing themselves a possibility of escape. Here, the RED agents fight to death. As the model is only used to determine the performance of future combat systems and most BLUE casualties occur at the beginning of the battle, the unrealistic behavior does not influence the results and interactions of this study.

b. Modeling

The RED agents can open fire at their maximal weapon range as soon as BLUE agents are detected. With this behavior they would lose their advantage of surprise and would have no great chance to inflict casualties. Therefore, the weapon ranges of RED's long-range weapon systems are reduced in this phase so that the ambush starts with RED fire at close distances. To ensure that BLUE has a low probability of detecting the RED ambusher early, the concealment of the RED agents is high (97% plus terrain). After RED opens fire this advantage is lost. The RED agents use a canyon as their major cover which crosses the Highway 491 from west to east. So, this area is a natural ambush site.

As the terrain is relatively open besides the canyon, BLUE advances with the main battle tanks first. They get immediate support by indirect fire and their Apache air escorts as the air escorts stay close, if a force approaches a terrain with a high possibility of an ambush. The Bradley will release the infantry if it is taking fire and will provide cover fire. Tests have shown that the dispersion of the infantry is the most critical phase for BLUE as indirect area fire can cause mass casualties among the infantry. The BLUE infantry immediately attacks the known positions of the RED forces after being dismounted. After 30 minutes without firefight the Bradley picks up the infantry squad and resumes the attack with mounted infantry.

2. Phase 2: Hit and Run

The second phase of the battle consists of a long-range, precision attack of two RED MILAN anti-tank systems on BLUE while they are moving south on the highway to operation objective 1.

a. Unrealistic Behavior

Again, the ambusher would not attack an enemy force of such a superior strength without the possibility to withdraw. Here, the RED forces try to inflict as much damage as they can before they are killed or run out of ammunition.

b. Modeling

The concealment rate of the RED agents is very high. As there are only two agents they usually are not detected by any BLUE agent before they shoot. As the probability of a successful hit declines with the range, the MILAN agents hold their fire until BLUE is close to 3000 meters. After RED forces shoot they are usually detected and quickly destroyed.

c. Phase 1 and 2 Insight

An immediate and logical insight is that if the enemy tries to take advantage of a surprise attack and BLUE has sophisticated sensors like UAVs and superior fire power, RED is more successful if it uses a minimum number of troops with long-range weapons. Otherwise, RED can be detected before it launches the attack. So there is a tradeoff between the number of ambushers used, their expected inflicted damage and the possibility of getting detected early. It seems from the knowledge of the author that not even ambush-experienced Taliban groups are fully aware of this simple concept in their considerations for an ambush force and used equipment.

3. Phase 3: Main Battle

In the third phase, the conventional warfare aspect is modeled. All RED forces have communication links to their company headquarters and share a common information picture. RED consists of a combined arms team with infantry, mines, long range anti-tank weapons, heavy mortars for indirect fire support, air defense, and a heavy battle tank reserve. RED fights from prepared and concealed positions according to their tactical doctrine as described in the TRADOC scenario.

The BLUE forces had normally already suffered casualties in the first two phases when they reach the third phase. This aspect increases the variability of the result for this phase, which is desired. It implements the consideration that if a battle takes place in reality, the actual available forces can be less than the nominal strength of the unit. Furthermore, the availability of the air assets ranges from low to high due to the duration of the first two phases. It could be that the air assets already took casualties and are no longer available. The battle order of the BLUE forces is different from time to time depending on the other phases. While testing the scenario, the author found that the agents are able to adjust their behavior realistically to the occurring situation within their given rules.

When the BLUE forces arrive, RED agents from Infantry Group 2 detect the BLUE agents, and long range anti-tank weapons open fire acting as the security force of the minefield. RED infantry is able to give target information to the heavy mortars, and the mortars are able to aim at the enemy with unarmored infantry first. When the BLUE agents further advance the counterattack of the RED T90M tank platoon is triggered. The T90M usually causing much damage especially when they are able to fire with their long-range missiles. When the BLUE agents get through the northern position concentrated and with enough combat strength left, they are able to destroy the infantry in the last position and get to the objective. In some cases when the BLUE forces had split up or had already taken too many casualties, they could not prevent RED Infantry Group 3 from holding their position and achieving a tactical victory for RED.

H. ADDITIONAL MODELING CONSIDERATIONS

1. Communications

All BLUE MANA squads have a direct communication channel to the company HQ and report their position, friends, unknowns, and enemies. The company HQ provides them with information summaries. As the RAVEN UAV is an asset from the battalion, it has a time delay of five minutes. If artillery is requested it has a two minute time delay. These times are fast and represent functioning modern network warfare. Notice that even with a 100% reliable communication link, there is still the possibility of fratricide due to the delay of information. Only in the third phase do the RED agents have a similar communication network as here a conventional, sophisticated enemy is modeled.

2. Sensors

A sensor in MANA consists basically of two functions: detecting an object and classifying it. The probabilities for time between detection and probabilities for classifying an unknown detection are calculated according to the distance and the terrain. A “line of sight” calculation is made.

3. Infantry

All agents have separate sensors for infantry and vehicle agents to take into account that infantry is more difficult to detect. Well-trained infantry in prepared position are modeled to hide completely from enemy sensors until they open fire. The muzzle flash can be easily detected. So, the concealment rates of the terrain still apply after the first shot, but the personal concealment of the firing agent is reduced.

It is difficult to ensure that all dismounted infantry is picked up by the corresponding infantry carrier. The most practical solution is to set the “embussing range” to 1500 meters. In case an infantry carrier is destroyed and the corresponding BLUE infantry is still alive, the infantry is ordered to attack dismounted toward the mission goal. It is not possible to reassign them to other carriers.

4. M1 Abrams Battle Tanks

The main battle tanks follow the Highway 491 to the south. Whenever they get shot at they go into a combat mode, slow their speed down and try to attack the enemy at distances over 500 meters. The tanks are modeled to keep close distances as a platoon and advance together with the infantry vehicles to provide mutual cover.

5. T90M Counterattack

The counterattack of the T90M takes place in a heavy terrain where they are able to use their long-range weapon systems. In reality, detailed preparation and reconnaissance is needed to judge if the counterattack is possible in the real terrain. As this was not possible, the terrain is modeled to enable the attack.

6. Artillery

Modern artillery has the ability to detect enemy artillery fire almost immediately, and the first priority is to destroy enemy artillery whenever the position is known. Therefore, the RED indirect fire agents lose their concealment after their first shots, and the fire logic of the BLUE artillery has priority for the RED artillery agents.

7. Breaking Points

Historically, battles are seldom fought until one side is completely annihilated. Especially in asymmetric scenarios like Afghanistan or Iraq, the BLUE (i.e., coalition forces) would not risk heavy casualties to avoid losing the public's support of the war. In this scenario neither BLUE nor RED has a breaking point, and both fight to the end. Even considered as nonrealistic behavior it is modeled by purpose. The more intense fight is expected to give better insights into the relationships between the input factors of a new ground combat system.

8. Stopping Conditions

MANA uses stopping conditions to automatically end a run. The chosen stopping conditions for the scenario include the following:

- RED has lost 69 agents;
- BLUE has lost 35 agents;
- The BLUE tanks reach the mission goal; or
- The maximum time of 50000 time steps (approximately 14 combat hours) is reached as after about this time “fresh” forces would substitute the exhausted BLUE force.

The chosen casualty thresholds for BLUE and RED are not their total agent number. The reason for this is that it is not possible to end the battle if BLUE has only the company headquarters and the artillery agent left, or when there is a single infantry soldier reaching the objective. Both cannot be considered a BLUE victory.

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V. BASELINE SCENARIO ANALYSIS

The baseline scenario is supposed to be a reference for the interpretation of the performance results for the possible future GCVs in the simulation runs. It is also possible to test the results for validity. Using his knowledge gained in modern combat, the author examined the baseline scenario runs to determine whether realistic relationships could be deduced from the results. It is also important to see how long the scenario run times are and how large the variance of the MOE are, and to use the variance results for power calculations to determine a sufficient number of replications for the DOE.

The basic scenario is chosen to run with a resolution of one second per time step and ten meters for LOS calculations. As MANA is a time step model, results depended on the chosen time step size. For example, in every time step, each agent is tested to see whether it detects a certain object. Several tests have been made running the scenario with lower time step resolutions than one second. The author watched the behavior of the agents during these runs. If the time steps were greater than five seconds, unrealistic patterns were detected (such as infantry was not picked up by the carriers and had to go on dismounted). It was determined that a resolution of one second gives reliable results. Detection and classification rates have been modeled accordingly. A ten meter resolution has been chosen due to similar experiments and due to the advice of Research Assistant Mary McDonald, who has years of experience with the software.

The runtime according to the settings on an ASUSTek Laptop (with Intel® Core i5 CPU M450 @ 2.40 GHz) are a maximum of 35 minutes per run as a simulation run ends when it reaches its maximum of 50000 time steps. So, computers are able to run replications in a reasonable amount of time. For the available cluster it takes on average 315 seconds for one node to perform a single replication. This, multiplied by 1000, but divided by the number of processors (68), yields to 1.3 hours for 1000 replications at one design point.

A. REFERENCE ANALYSIS

The casualties of BLUE and RED in the base scenario for 1000 replications are shown in Figure 15 and Table 5. While RED gets annihilated most of the time (90% casualties), BLUE has to pay for this result with a casualty rate of 50%. The most casualties in numbers occur for the RED infantry, which is not surprising as they are the most numerous and one of the least protected forces on the battlefield. Interestingly, there is a direct comparison with the similar modeled BLUE infantry. Due to their much better support by armored vehicles, CAS and indirect fire, their loss expectance is only half of what it is for a RED infantry solder–even when the RED infantry has the advantage of concealment and cover. In other words, even when considered inferior in a direct comparison the survivability of BLUE infantry is higher due to the surrounding force structure.

Another aspect of importance, especially for Western democracies, is the number of wounded and killed soldiers. MANA only counts killed agents. The number of soldiers taken out of action must be calculated according to the number of soldiers which are represented by each agent. In total numbers, BLUE lost an average of 31 soldiers in each battle while RED lost 78. This results in an exchange rate of about 1:2.5 in favor of BLUE.

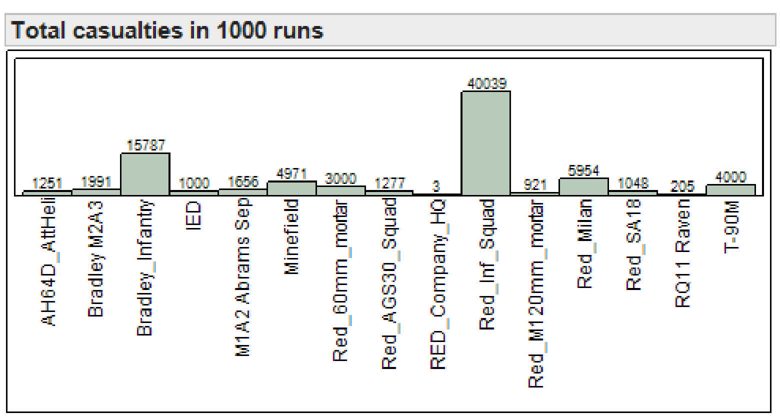


Figure 15. Histogram of the casualties for 1000 replications. The x-axis shows the type of casualties.

Table 5. Summary statistics for the casualties of 1000 replications. "Agents killed" shows the total number of casualties; "Percentage lost" gives an average of how many agents were killed; "Soldiers lost" calculates the corresponding number of soldiers dead.

Type of casualty	Agents killed	Percentage lost	Soldiers lost
RQ11 Raven	205	20.5	0
AH64D_AttHeli	1251	62.6	2502
Bradley M2A3	1991	49.8	5973
Bradley_Infantry	15787	56.4	15787
M1A2 Abrams Sep	1656	41.4	6624
IED	1000	100	0
Minefield	4971	82.9	0
RED_60mm_mortar	3000	100	3000
RED_AGS30_Squad	1277	31.9	2554
RED_Company_HQ	3	0.3	30
RED_Inf_Squad	40039	93.1	40039
RED_M120mm_mortar	921	92.1	3684
RED_Milan	5954	99.2	11908
RED_SA18	1048	52.4	1048
T-90M	4000	100	16000
Total RED	**62213**	**87.6**	**78263**
Total BLUE	**20890**	**53.6**	**30886**
Total	**83103**	**75.5**	**2.53 Ratio**

Another overview is given in Figure 16, which shows the number of casualties inflicted by each type of system or soldier. Artillery and close air support (CAS) through Apaches are the primary contributors to RED casualties in the MANA scenario.

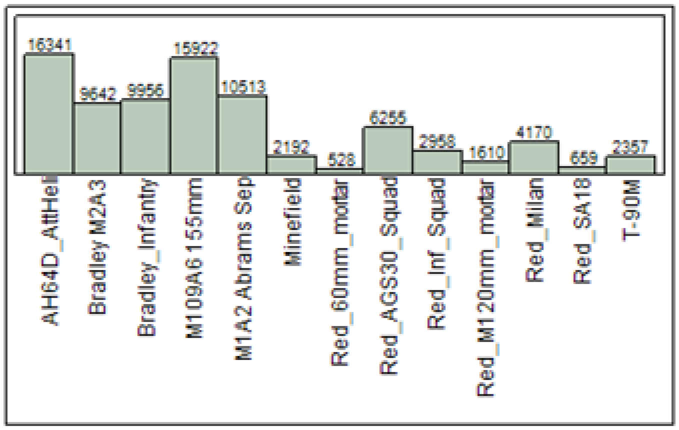


Figure 16. Histogram of casualties inflicted by the different types of systems.

TRADOC simulated the underlying scenario with the Advanced Warfighting Simulation (AWARS) software at the division level with similar force structures. A comparison is done to give some additional hints as to whether the MANA model has reasonable results.

First, the importance of the artillery matches up with TRADOC's results. The casualties inflicted by the Apaches are also in accordance with AWARS's results, and even the distribution of the killed targets matches due a similar composition of the enemy. Not included in the comparison are casualties of logistic units as they are not modeled in MANA. As the RED force uses more advanced weapons than in the original TRADOC scenario and many of the simulated combatants fight-to-the-end without trying to conserve combat power for follow on missions, the logical conclusion is that the RED and BLUE casualty levels must be higher. RED is able to inflict a worse casualty exchange rate from BLUE's perspective. The TRADOC simulation estimates that about 10000 RED soldiers are killed for a loss of 1100 BLUEs. This is an exchange rate of about 9:1 against a 2.5:1 ratio for the MANA scenario. RED inflicted about 10% losses on the BLUE force while suffering about 20% to 30% losses in AWARS, which represents the assumed differences. (TRADOC, 2009)

TRADOC results and major insights (TRADOC, 2009) include the following:

a. Both the Coalition and the Threat forces can claim a “victory in this scenario. The Coalition forces achieved their main objective of restoring the international border, and their units did not lose substantial combat power (lowest strength brigade was at 87% aggregate strength at the end of the run). The Threat forces achieved their goal of preserving combat power for their Phase II (infantry battalions at 76%). They also inflicted over 1,100 troop losses to Coalition forces.

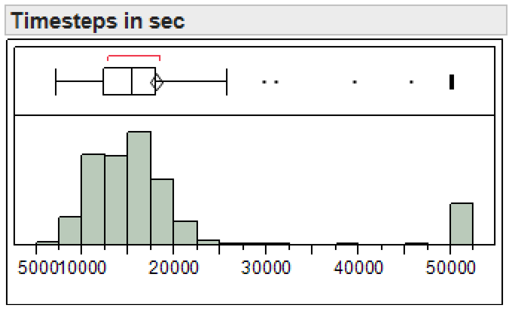
b. The Threat’s ability to avoid detection in complex terrain allows them to degrade the Coalition standoff advantage and to preserve forces for Phase II.

c. The Threat infantry division can inflict casualties to BLUE’s mechanized forces. Their tactics allow them to draw Coalition forces into close combat in complex terrain where their infantry weapons are effective against all Coalition systems at close ranges. Heavy machine guns are effective against armored vehicles except tanks. The Threat infantry is also equipped with a variety of anti-tank guided missiles which prove effective against Coalition tanks.

d. An extensive obstacle plan enables Threat forces to delay the / DIV advance by 24-48 hours. However, their plan did not include the 11 DP IN DIV exploiting this delay in any way.

In analyzing the comparison results, we can see that the conclusion that both “forces can claim a ‘victory’ in this scenario” holds true. Both forces have similar casualty distributions. In our run, RED agents do not try to avoid detection, and so, TRADOC insight “b.” is not applicable for comparison. On the other hand, the third TRADOC insight that the “Threat infantry division can inflict casualties to mechanized forces” is fully emphasized by the MANA scenario, which obtains the same results. Finally, the mines and IEDs used in the MANA scenario cause BLUE to take much more time to reach their goals. BLUE needs approximately one hour (distance through speed) in an unopposed scenario, while the baseline scenario requires five hours ± 13 minutes with a confidence of 95% and 1000 replications (see Figure 17). So, TRADOC insight “d.” matches the MANA scenario.

A histogram of the observed battle duration of each run and summary statistics are shown in Figure 17. As can be seen from the plot, the battle duration has an approximated normal distribution around the mean of 18000 seconds and another peak at exactly 50000 seconds for the runs which are stopped by the time limit of 50000 seconds per battle.



Summary Statistics

Mean	18045.201
Std Dev	10580.217
Std Err Mean	334.57582
Upper 95% Mean	18701.753
Lower 95% Mean	17388.649
N	1000

Figure 17. Battle Time in seconds: the attached summary statistics describe the observed values according to the mean and the variance (here called *"Standard deviation"* and *"Standard Error Mean"); "Upper and lower 95% Mean"* gives a calculated 95% confidence interval for the observed mean, and *"N"* stands for the number of replications.

Appendix B contains more detailed data from the basic scenario. This data has been analyzed by the author to find "bugs," unrealistic behavior or infeasible outcomes, such as helicopters destroyed by mines. As none were found the author is confident that the result represents a realistic, intense fight where the right basic relationships exist and insights can be gleaned.

BLUE's mission goal is to destroy the RED forces or to break through and reach the mission objective with a sufficiently large force. RED's objective is to inflict as many casualties on BLUE as possible. Normally, breaking points are reached much earlier, but with the special setting of the scenario (to fight until one side is totally annihilated) the author chose to set following victory conditions.

Victory definitions:

- (69 RED casualties **or** BLUE tanks reached objectives) **and** less than **25** BLUE casualties => 655 BLUE victories
- 25 or more BLUE casualties => 327 RED victories
- less than 69 RED casualties **and** less than 25 BLUE casualties **and** BLUE did not reach his objective => 18 draws

As there are no breaking points for the forces, the draws resulted from the fact that the simulation stopped at the time limit without one side reaching its goals.

With less than 25 casualties, BLUE has about one-third of its combat power left. In other words, BLUE could lose two-thirds of its combat strength and still achieve a victory. For the purpose of this thesis, this is a reasonable definition even when it is more than questionable that a Western democracy would attack with such an expected loss rate.

As there are times when enemy agents remain after the battle time reaches its maximum value, the one MOE for the casualties should be a casualty ratio. The results for the defined MOEs in Chapter IV are shown in Table 6.

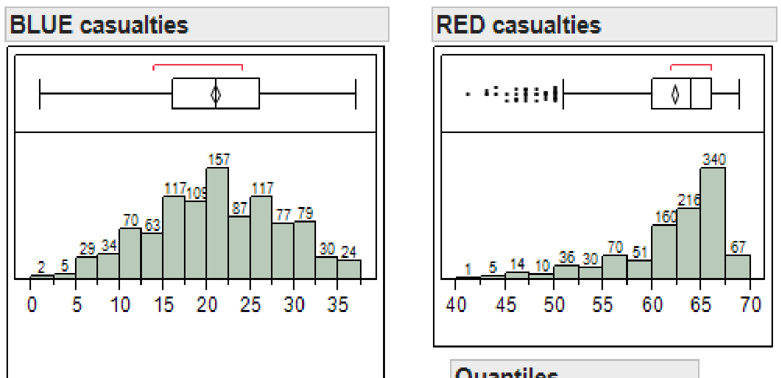
Table 6. Overview for the MOEs in the basic scenario with 1000 runs.

	BLUE casualty [agents]	**RED casualty [agents]**	**Battle time [min]**	**Casualty ratio**	**Killed Bradley [agents]**	**Killed BLUE inf. [agents]**	**Killed M1 Abrams [agents]**	**BLUE victories**
mean	20.89	62.21	300.75	3.63	1.99	15.79	1.66	65%
95% CI	[20.44, 21.34]	[61.90, 62.53]	[289.81, 311.70]	[3.44, 3.81]	[1.91, 2.07]	[15.34, 16.23]	[1.58, 1.73]	[62%, 68%]

Notice that especially the BLUE casualties have a high variance, which has to be taken into consideration for the number of replications per design point necessary.

B. POWER CALCULATIONS

One of the purposes for the baseline runs is to estimate the variability of the casualty rates for the scenario. The BLUE and RED agents killed per battle are summed up and the standard deviations σ_B and σ_R are calculated. The results are shown in Figure 18.



BLUE casualties

Quantiles		
100.0%	maximum	37
99.5%		37
97.5%		34
90.0%		31
75.0%	quartile	26
50.0%	median	21
25.0%	quartile	16
10.0%		11
2.5%		7
0.5%		4
0.0%	minimum	1

Summary Statistics	
Mean	20.89
Std Dev	7.3180225
Std Err Mean	0.2314162
Upper 95% Mean	21.344118
Lower 95% Mean	20.435882
N	1000

RED casualties

Quantiles		
100.0%	maximum	69
99.5%		69
97.5%		68
90.0%		67
75.0%	quartile	66
50.0%	median	64
25.0%	quartile	60
10.0%		55
2.5%		49
0.5%		44
0.0%	minimum	41

Summary Statistics	
Mean	62.213
Std Dev	5.0714249
Std Err Mean	0.1603725
Upper 95% Mean	62.527706
Lower 95% Mean	61.898294
N	1000

Figure 18. BLUE and RED casualties.

Note that the “quantiles” in Figure 18 are another measure of how many observations fall in a certain range. The quantiles also describe the distribution of these observations.

From Figure 18, it can be seen that the maximum number of BLUE casualties is 37 even though BLUE has 39 agents. The reason is that the BLUE

Company Headquarters and the BLUE artillery are out of reach for the RED forces and cannot be attacked. More importantly, due to the high variability of the BLUE casualties a 95% confidence interval has a width of .45 casualties for 1000 replications. If a margin of error is set to +/-1 casualties and a 95% confidence is desired, the following calculations for the number of replications needed per design point result (Devore, 2011):

$\mathbf{1.96} * \frac{\boldsymbol{s}}{\sqrt{\boldsymbol{n}}} = \mathbf{1}$ *with s = 7.32 (estimator for the true standard deviation)*

n= 206.

That leads to the conclusion that in the DOE phase at least 206 replications per design point are necessary to achieve a statistical resolution of one casualty difference with 95% confidence. The calculation is explicitly done for the number of BLUE casualties because they have the highest variance. As battles usually have the highest variance near parity conditions, the variance is expected to be reduced when the BLUE forces are improved by new weapon systems as this factor shifts the battle away from parity (Hillestad, Owen, & Blumenthal, 1993).

For the RED casualties the variance is smaller, and the half-width of a 95% confidence interval is only .3 for 1000 replications. For the battle duration a half-width of 13 minutes for a 95% confidence interval is calculated.

As the author wants to use statistical tests to estimate if there is a difference in the means between casualties; *type-2* errors have to be accounted for. The sample size calculation is done by the following formula (Devore, 2011):

$$\mathrm{n} = \left(\frac{\sigma * (z_\alpha + z_\beta)}{\mu_o - \mu_a}\right)^2.$$

Drawing different beta values, which represent the power, leads to Figure 19. The power value represents how likely it is to reject the null hypothesis if it is not correct, or in other words, not to commit a type-2 error. Note that the colored lines in Figure 19 show the different power for a given resolution and given number of replications.

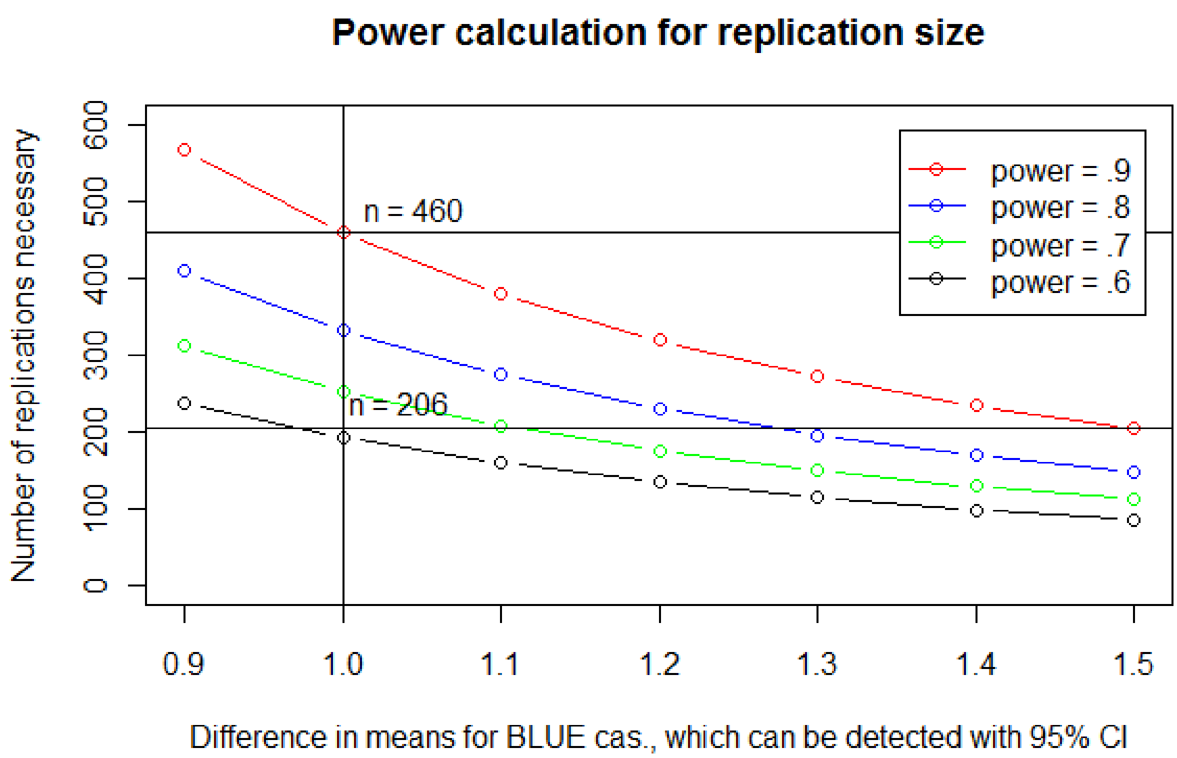


Figure 19. Power calculation for replication size.

C. CONCLUSIONS

When improvement of the BLUE force is considered, that is, at least one fewer BLUE agent gets killed per battle (or one more RED agent is killed per battle), a required power for statistical tests of .9 leads to the consequence that the DOE should have about 460 replications per design point. With 206 design points a resolution of +-1.5 is achievable at the same power level.

To get a better estimate of how changes in agents affects the scenario, the author chose to alter the sensor of the modeled RAVEN UAV for infantry detection from the data shown in Table 7 to an immediate detection for the UAV sensors up to 4000 meters with a constant classify probability of 0.2. In the new scenario 1000 replications were performed. The change altered the expected number of BLUE casualties from 20.89 to 20.16 and increased the RED casualties from 62.213 to 62.73. If this is already a statistically relevant difference, it can be tested by a t-test.

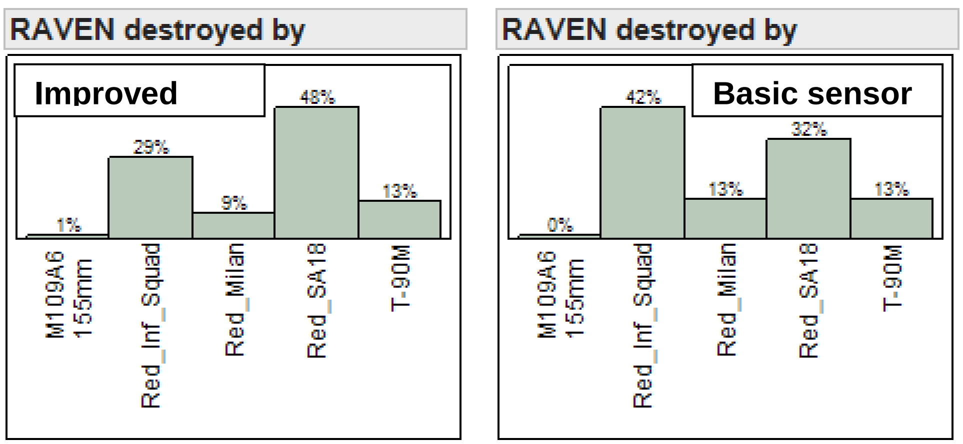
A t-test uses statistical calculations to test the theory that the means for a given sample size and variance are the same. As statistics only estimate the population, there is no result obtained with absolute certainty. Usually, the test threshold is chosen at a 95% confidence level. This goal is reached if the resulting *p-value* of the test is below 0.05. For the BLUE casualties the result is *p-value* = 0.02737 and a *p-value* = 0.01961 for the RED casualties. This shows that the hypothesis that the means of the casualties for BLUE and RED forces are equal can be rejected within the chosen confidence. So, we conclude that difference between the means has changed.

Notice that every difference can be statistically relevant if the sample size is big enough. For 460 replications a difference of 1 would be needed, as can be seen in the previous paragraph. A reduced casualty expectance of 0.7 for BLUE corresponds to about 4% of the whole casualties. The difference achievable by 460 replications is about 5%.

Table 7. The average time between detection and classification probabilities for the RAVEN infantry sensor in the basic scenario.

range	**50**	**2000**	**4000**	**6000**
Average time between detection	0	0	5	10
Probability of classification given detection	0.2	0.1	0.01	0.005

The author expected that the exchange rate is more favorable for BLUE, which is proven. Unexpected was the finding that the incidents of fratricide are reduced by a better situational awareness of the BLUE agents. So, in the altered scenario, no fratricide at all occurred from Apache helicopters on Bradley or BLUE infantry. Overall, the simulation shows that the improved UAV sensor increases the situational awareness of all BLUE agents, which leads to a higher BLUE survivability and lethality. The relationships between the agents according to lethality and survivability are obtained, as can be seen in Appendix B. The only exception occurred for the UAV itself, as is shown in Figure 20.



Frequencies (Improved)

Level	Count	Prob
M109A6 155mm	2	0.01010
Red_Inf_Squad	58	0.29293
Red_Milan	17	0.08586
Red_SA18	95	0.47980
T-90M	26	0.13131
Total	198	1.00000

N Missing 0
5 Levels

Frequencies (Basic sensor)

Level	Count	Prob
M109A6 155mm	1	0.00488
Red_Inf_Squad	87	0.42439
Red_Milan	26	0.12683
Red_SA18	65	0.31707
T-90M	26	0.12683
Total	205	1.00000

N Missing 0
5 Levels

Figure 20. RAVEN survivability comparison: improved sensors (left); basic sensors (right).

It can be seen that the number of UAVs killed by RED infantry is decreased as the UAV can avoid small arms fire of the RED infantry better with improved sensors.

VI. DESIGN OF EXPERIMENTS

The analysis of the results from the DOE setup over multiple analysis tools used to gain insight is provided in this chapter. First, this is done for an infantry carrier CGV. After that, the steps are repeated for a main battle tank GCV. In the end both sets of results are compared, and additional insights are stated.

A. DESIGN OF EXPERIMENT IMPLEMENTATION

To implement a DOE for a MANA scenario, the steps detailed in the following paragraphs have to be conducted.

1. Define Factors

Factors with ranges based on the analysis in Chapter II are defined as continuous, discrete, or binary. Some of the factors (weapons and sensors) are data tables. These tables are modeled with one continuous factor. To give an example, the detection sensor for infantry has following underlying data table (see Table 8) for the modeled Bradley agents.

Table 8. Data table for the infantry detection sensor modeled for the Bradley infantry carrier.

Sensor Inf						
Detection	Range	1	1000	2000	3000	4000
	Avg Time between	0	0	5	10	15
Classify	Range	1	-	2000	3000	4000
	Prob/Turn	1	-	1	0.7	0.5
Class	2 (infantry)					

To turn the table into a factor, the ranges for detection and classification are multiplied by a continuous value while the corresponding average time between detection and the probabilities for classification are kept constant.

Weapons systems and sensor types can be installed on the GCV or left off, which is controlled by a binary factor.

2. Enter DOE Factors in DOE Tool

The defined factors are entered in an already developed DOE development tool. For the analysis, a Nearly Orthogonal Latin Hypercube (NOLH) design developed by Prof. Susan M. Sanchez from the NPS Department of Operations Research is used (S. Sanchez, 2011).

3. Analyze Interactions and Dependencies between Factors

The benefit of such a design is that it allows the analyst to alter all factors at the same time and avoids high correlations between them. It also allows for the exploration of the multidimensional answer-space with a “space-filling design” without using an impracticable amount of design points. To restate it more simply: The NOLH design allows analyzing the interactions and dependencies between the factors by carefully choosing the combinations of the factor values according to a mathematical process so that there are no large gaps in the factor value combinations. To give an example, a 14 factor full design where every factor can only have two values would have 2^{14} possibilities, which results in 16384 design points. Given the calculated necessary 460 replications, this would mean 7.5 million runs, which would take on the available cluster 314 days of runtime. With the NOLH it is possible to do a comparable analysis with 65 carefully selected design points, which leads to 29900 total simulated battles. This experimental set can be done in less than three days on the computing cluster (Cioppa & Lucas, 2007).

4. Collect Results

After the DOE is setup, a spreadsheet file containing the design is turned into a batch file which then controls the cluster runs. The produced results are then combined in one excel.csv file. This thesis used a combination of JMP, R and Microsoft Excel as tools to analyze the output data.

B. INFANTRY CARRIER

1. Implemented DOE and Data Validation

The first analyzed GCV is an infantry carrier. Therefore, the modeled Bradley platoon is substituted by the imaginary GCV with different tangibles and physical factors. To achieve comparability, the behavior, tactics used and the orders given to the GCV are exactly the same as for the Bradley platoon. Also, the number of vehicles modeled remains the same. The 14 factors shown in Table 9 are varied in the DOE.

Table 9. Used factors for infantry carrier DOE; ranges deduced from results in Chapter II. The first column is the factor name; the second is the squad in the MANA scenario to which the factor is applied. The remarks column specifies which attribute of a data table is to be varied. The variable class is necessary for specifying the factor type for the DOE.

Infantry carrier			Ranges				
			lower	current	upper	Variable class	Unit
	Squad Number	Remarks/applied on					
Number of Hits	4, 14, 15, 16		1	1	3	discrete	
Concealment	4, 14, 15, 16		0	0	99	continious	
Speed	4, 14, 15, 16		40	50	60	continious	km/h
Armor	4, 14, 15, 16		300	500	1000	continious	mm RHA
Number of Inf	5, 11, 12, 13	no of agents in squad	7	7	12	discrete	
DetectionInf*	4, 14, 15, 16 (sensor1)	range for detection and classification	0.8	1	2	continious	DataTable
DetectionVeh*	4, 14, 15, 16 (sensor2)	range for detection and classification	0.8	1	2	continious	DataTable
Bushmaster*	4, 14, 15, 16 (weapon1)	only on range	0.8	1	2	continious	DataTable
*MG**	4, 14, 15, 16 (weapon2)	only on range	0.8	1	2	continious	DataTable
TOW*	4, 14, 15, 16 (weapon3)	on range and on penetration	0.8	1	2	continious	DataTable
Mortar*	4, 14, 15, 16 (weapon4)	if weapon is added or not	0	0	1	discrete	binary
Centric Wareface	8 (sensor1)	AvgTime between detection	0.01	1	1	continious	
EW	24 (all comlinks)	Reliability	0.01	1	1	continious	
Active Defense	1,2,21,26(weapon1); 6,17,18 (weapon4); 23 (weapon1,3)	Hit probability	0.2	1	1	continious	

* The factor has a data table representation.

Additional remarks related to Table 9.

- Factor Centric Warfare: Summarized effects of advanced reconnaissance assets and a functioning information distribution process. A value of 1 means that the BLUE external reconnaissance assets are excellent. Most RED agents are detected upfront, and the information is passed down the command chain to every BLUE agent immediately. A value of 0.01 means that the BLUE Company has to rely totally on its own sensor platforms.

- Factor Electromagnetic Warfare (EW): Here the effects of EW on the enemy network in phase 3 of the battle are modeled. It starts from a perfectly reliable network for the RED agents represented by the value 1 to a nearly useless network where only 1% of the reports about detections of BLUE agents are transmitted. This affects the RED ability to use indirect fire in particular.
- Factor Active Defense: Simulates hard and soft kill systems which protect vehicles and nearby infantry; therefore, the hit probability of the enemy anti-tank weapons is reduced by 20% of the basic hit probability. A value of 0.2 means that the active defense systems can destroy 80% of all incoming anti-tank missiles.

The DOE for these factors is given in Appendix C and consists of 65 design points. The design points also represent the degrees of freedom (DF) available for creating a meta-model of the data. As two DF are already consumed by the usual error and variance estimation, only 63 factors can be implemented in any of the following meta-models.

2. Data Validation of the Output File

Data validation on the output file consists of several steps before analysis:

- Check the data file for completeness as well as for corrupted and missing entries.
- Check the design by examining the distribution of the factors. Has the design been implemented in the correct way, and how are the values of the factors distributed? For example, the histograms in Figure 21 show the factors for the number of infantry carried per GCV and the continuous multiplier of the GCV sensor used for detecting enemy infantry.
- The "space filling" behavior of the DOE can be seen by elevating the scatterplots. If the factor is not discrete the points cover the whole area in about equal distances. The scatterplots also show correlation between the factors. If the RED lines are flat, the correlation is low. (See Figure 22.)

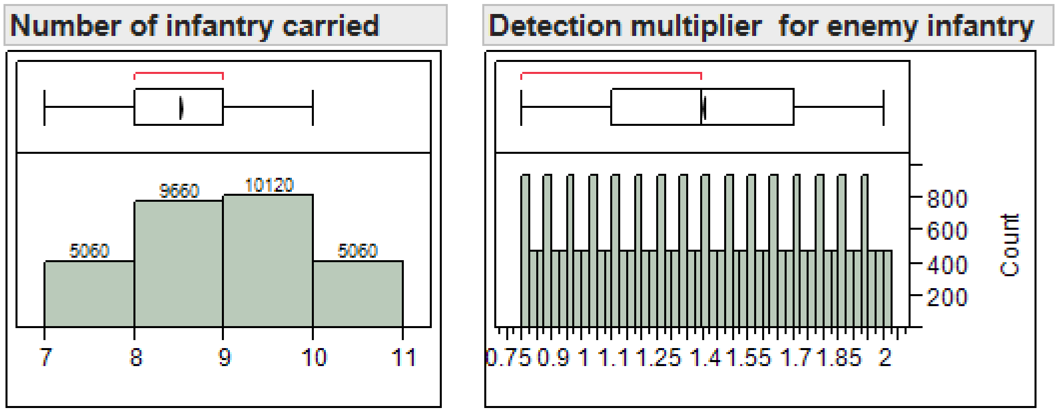


Figure 21. Histograms for the frequency of factor values. The left histogram shows a discrete factor (how many soldiers are carried by the GCV) and the right one shows a continuous one (which multiplies the ranges for the data table of the modeled GCV infantry sensor). As can be seen by the left histogram, the number of infantry carried is unequally distributed between 7 and 10. This is not a problem as long as there are enough design points for the fitting of meta-models. The inequality is introduced by "balancing" the DOE and because the 65 design points cannot be divided equally by four. The right histogram shows that for a continuous factor the values are equally distributed over the whole range.

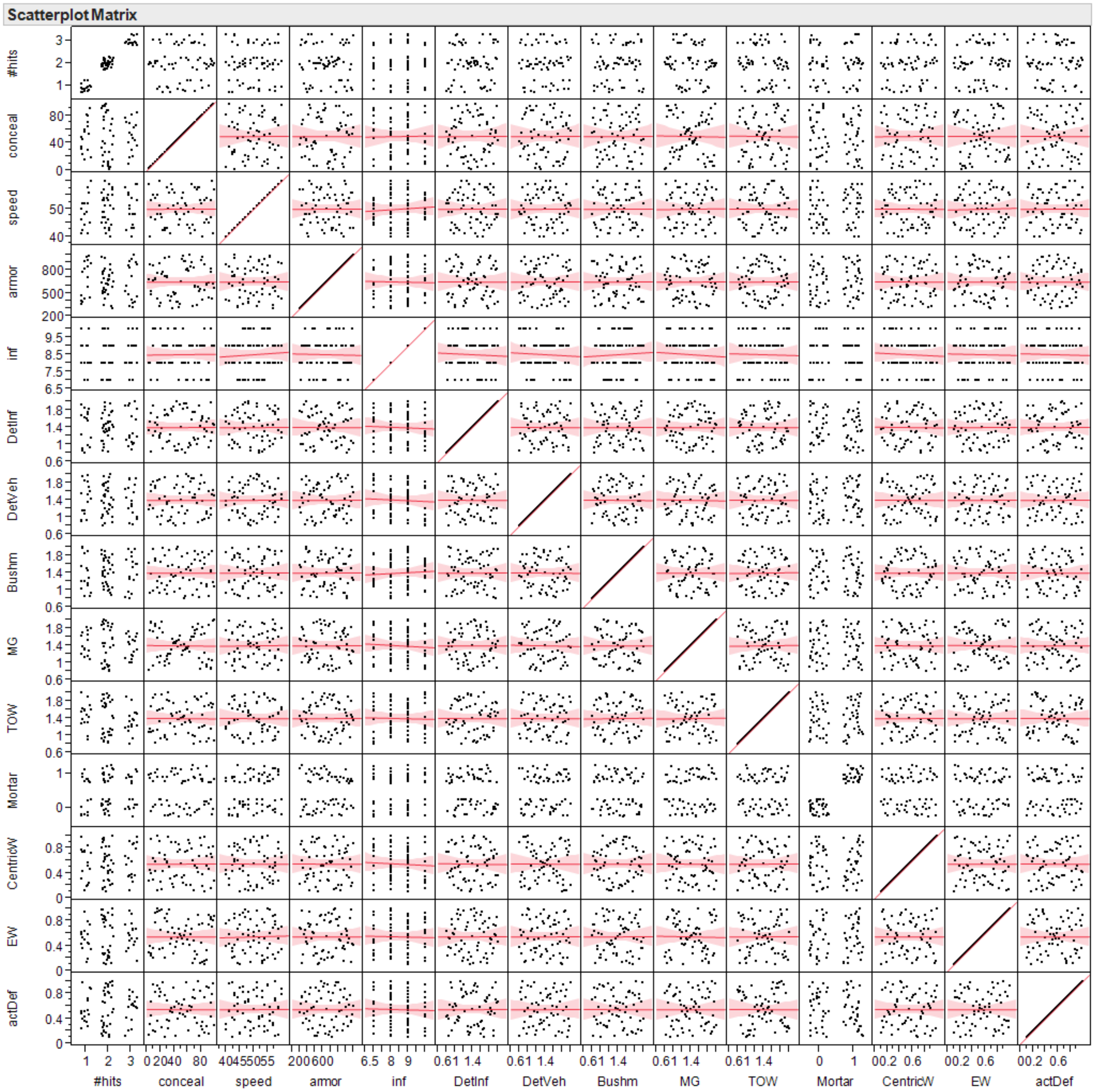


Figure 22. Scatterplot matrix. All factors are shown to identify space-filling and correlation behavior of the DOE. For the discrete factors “#hits,” “inf,” and “mortar” the points cannot be space filling as they are fixed by the discrete values.

The data passed all checks and can therefore be used for regression analysis.

3. Correlation of the MOEs

The next step is to test the MOEs defined in Chapter IV to see if they are correlated. A high correlation means that the correlated MOEs can be combined, and the same insight can be gained by fewer MOEs. For GCV as infantry carrier, seven MOEs are defined, and their correlation is shown as values in Table 10 and graphically in Figure 23. The correlation can be positive or negative to combine MOEs. The threshold can be set by the analyst. Here, the author chose to set it to 0.7 as this threshold has been used in similar problems in lectures at NPS.

Table 10. Correlation coefficients; the defined threshold of 0.7 is exceeded for "Inf_Cas" with "BLUE_Cas" and for "BLUE_victory" with "BLUE_Cas" as well as for "BLUE_Victory" with "Inf_Cas". Missing values result from cases where no BLUE casualties occurred so the casualty ratio could not be calculated.

Correlations

	Alleg1Cas(Blue)	Alleg2Cas(Red)	Steps	MOE_cas_ratio	GCV_cas	Inf_Cas	BLUE_victory
Alleg1Cas(Blue)	1.0000	-0.0863	0.3051	-0.6009	-0.0035	0.9845	-0.7920
Alleg2Cas(Red)	-0.0863	1.0000	0.1053	0.1147	-0.2897	-0.0300	0.0731
Steps	0.3051	0.1053	1.0000	-0.2449	-0.0591	0.2847	-0.2180
MOE_cas_ratio	-0.6009	0.1147	-0.2449	1.0000	-0.0671	-0.5775	0.3103
GCV_cas	-0.0035	-0.2897	-0.0591	-0.0671	1.0000	-0.1037	0.0422
Inf_Cas	0.9845	-0.0300	0.2847	-0.5775	-0.1037	1.0000	-0.7838
BLUE_victory	-0.7920	0.0731	-0.2180	0.3103	0.0422	-0.7838	1.0000

There are 65 missing values. The correlations are estimated by Pairwise method.

From Table 10 and Figure 23 it can be deduced that "BLUE_victory" and infantry casualties were highly correlated with the total BLUE casualties. While this correlation was expected between "BLUE victory" and "BLUE casualties" the nearly perfect correlation between infantry casualties and total casualties shows that infantry casualties are the major part of the whole casualties, and whenever casualties get heavy there is also a high number of infantry killed. The final result from this analysis is that the MOE "BLUE victory" and "BLUE infantry casualties" are not necessary because this information is contained in the MOE "BLUE casualty."

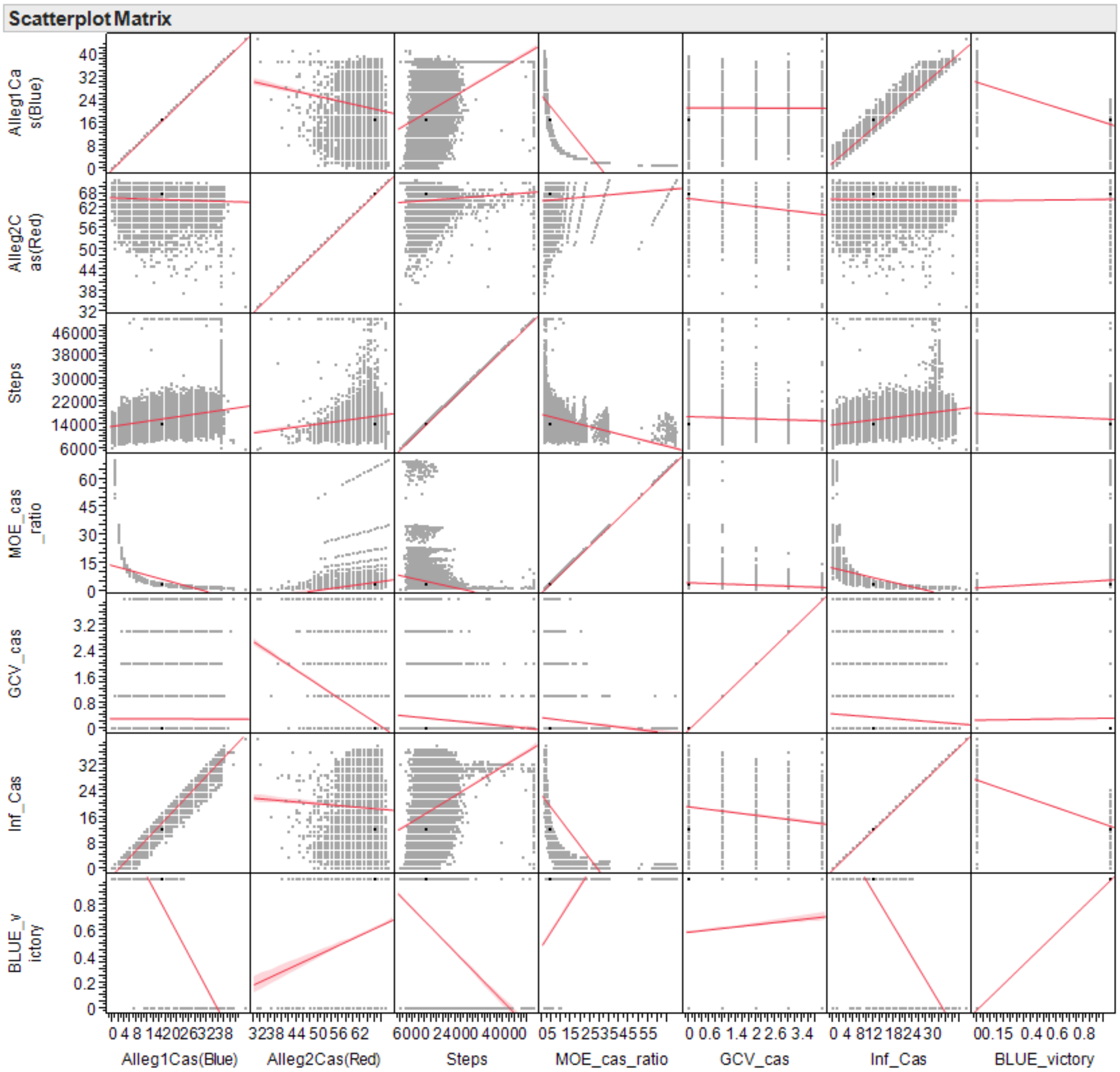


Figure 23. Correlation between MOEs. If a RED line is nearly horizontal, no significant correlation occurs. If it increases, it is positively correlated; if it decreases, it is negatively correlated.

4. Factor Screening

In the following sections, the major contributors to the MOEs, including interaction and non-linear effects, are examined to find accurate meta-models. For more practical use and explanation, the number of included factors should be minimized. The regression techniques used are based on the principal to minimize the sum of square errors (Montgomery, Peck, & Vining, 2012) by fitting the factors to an appropriate model. Regression basically fits a mathematical model with the input factors or independent variables so that the squared distances to all observed data points are minimized.

a. Main Effect Models

The first regression technique used is to fit simple main effect models for the MOEs. The reasoning behind this is that main effect models are easy to understand and interpret. The main effect models gained in several iterations are shown in Figures 24 through 26. The "summary of fit" tables give a value to how much observed variance is explained by the regression model, or more simply, how good the model fits the observations. The "sorted parameter" table shows the model itself. Each factor used is listed in the "term" column; its multiplier is stated in the "estimate" column together with an involved uncertainty stated in the "Std Error" column. The "t-ratio" and the "Prob > ItI" columns give statistical values if the term is necessary in the model. For example, the "Blue casualties" model estimates the number of infantry (= "inf") on a GCV as the most significant factor. If the number is increased by 1 the "Estimate" value of 2.16 says that the BLUE casualty expectance is increased by 2.16 agents. As there are four GCVs modeled, this means that 50% of the additional troops are killed.

BLUE casualties

Summary of Fit

RSquare	0.136806
RSquare Adj	0.136402
Root Mean Square Error	8.344612
Mean of Response	21.28642
Observations (or Sum Wgts)	29900

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
inf	2.1641375	0.05074	42.65	<.0001*
DetVeh	-4.089269	0.138567	-29.51	<.0001*
DetInf	-3.920164	0.138985	-28.21	<.0001*
conceal	-0.032856	0.001682	-19.53	<.0001*
Mortar	-1.538899	0.099896	-15.41	<.0001*
EW	-2.31925	0.183662	-12.63	<.0001*
TOW	1.2104529	0.138704	8.73	<.0001*
armor	0.0015962	0.000237	6.74	<.0001*
actDef	0.7515415	0.183657	4.09	<.0001*
#hits	0.2638672	0.069382	3.80	0.0001*
Bushm	0.3724776	0.138062	2.70	0.0070*
MG	-0.202976	0.137807	-1.47	0.1408
CentricW	0.2229503	0.183596	1.21	0.2246
speed	-0.003191	0.008298	-0.38	0.7006

RED casualties

Summary of Fit

RSquare	0.060535
RSquare Adj	0.060095
Root Mean Square Error	2.6844
Mean of Response	64.41632
Observations (or Sum Wgts)	29900

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Mortar	1.1071822	0.032136	34.45	<.0001*
DetInf	0.7894746	0.04471	17.66	<.0001*
#hits	0.3415143	0.02232	15.30	<.0001*
actDef	-0.636683	0.059081	-10.78	<.0001*
TOW	0.3615474	0.04462	8.10	<.0001*
conceal	-0.004339	0.000541	-8.02	<.0001*
armor	0.0003931	7.614e-5	5.16	<.0001*
DetVeh	-0.198943	0.044576	-4.46	<.0001*
inf	-0.026418	0.016323	-1.62	0.1056
CentricW	0.0947294	0.059061	1.60	0.1087
MG	-0.050581	0.044331	-1.14	0.2539
EW	-0.065176	0.059083	-1.10	0.2700
speed	-0.001462	0.002669	-0.55	0.5839
Bushm	0.0226772	0.044413	0.51	0.6096

Figure 24. The main effect models for BLUE and RED casualties.

Casualty ratio

Summary of Fit

RSquare	0.039836
RSquare Adj	0.039385
Root Mean Square Error	6.312442
Mean of Response	4.63997
Observations (or Sum Wgts)	29835

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Mortar	1.6425085	0.075656	21.71	<.0001*
DetInf	1.8962802	0.105259	18.02	<.0001*
conceal	0.0150088	0.001274	11.78	<.0001*
inf	-0.355795	0.038426	-9.26	<.0001*
DetVeh	0.8044196	0.104922	7.67	<.0001*
actDef	-1.02315	0.13906	-7.36	<.0001*
EW	0.9342039	0.139105	6.72	<.0001*
MG	0.4595049	0.104389	4.40	<.0001*
TOW	-0.421484	0.105049	-4.01	<.0001*
#hits	0.1249678	0.05253	2.38	0.0174*
Bushm	-0.193639	0.104527	-1.85	0.0640
armor	-0.00022	0.000179	-1.23	0.2193
speed	0.0036997	0.006285	0.59	0.5561
CentricW	-0.010009	0.139037	-0.07	0.9426

Battle duration

Summary of Fit

RSquare	0.083744
RSquare Adj	0.083315
Root Mean Square Error	4224.996
Mean of Response	16917.05
Observations (or Sum Wgts)	29900

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
conceal	-29.00581	0.851842	-34.05	<.0001*
DetVeh	-1681.489	70.15828	-23.97	<.0001*
#hits	533.07205	35.12903	15.17	<.0001*
DetInf	-977.7299	70.37002	-13.89	<.0001*
Mortar	-651.007	50.57879	-12.87	<.0001*
MG	-661.7997	69.77356	-9.48	<.0001*
speed	-38.30782	4.201403	-9.12	<.0001*
armor	0.8753966	0.119833	7.31	<.0001*
inf	-180.3934	25.69043	-7.02	<.0001*
EW	-517.4168	92.9907	-5.56	<.0001*
actDef	277.67296	92.98797	2.99	0.0028*
TOW	-177.8827	70.22785	-2.53	0.0113*
Bushm	-143.1141	69.90253	-2.05	0.0406*
CentricW	-12.3758	92.95726	-0.13	0.8941

Figure 25. The main effect models for casualty ratio and battle duration.

GCV casualties

Summary of Fit

RSquare	0.253534
RSquare Adj	0.253184
Root Mean Square Error	0.609609
Mean of Response	0.302441
Observations (or Sum Wgts)	29900

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
#hits	-0.437155	0.005069	-86.25	<.0001*
actDef	0.4289595	0.013417	31.97	<.0001*
armor	-0.000476	1.729e-5	-27.52	<.0001*
TOW	-0.232322	0.010133	-22.93	<.0001*
Mortar	-0.154393	0.007298	-21.16	<.0001*
conceal	-0.002268	0.000123	-18.45	<.0001*
speed	0.0068201	0.000606	11.25	<.0001*
DetInf	-0.089041	0.010153	-8.77	<.0001*
CentricW	0.0560085	0.013412	4.18	<.0001*
DetVeh	-0.022216	0.010123	-2.19	0.0282*
EW	-0.019784	0.013417	-1.47	0.1404
Bushm	0.0142736	0.010086	1.42	0.1570
MG	-0.005984	0.010067	-0.59	0.5523
inf	-0.00053	0.003707	-0.14	0.8862

Figure 26. The main effect models for the GCV casualties.

b. Analysis of Main Effect Models

As can be seen from the "Summary of Fits" the R-square values are very low. The interpretation is that even when all underlying factors are known the outcome and duration of the battle cannot be predicted as only 4–14% of the variance can be explained. This issue is resolved by calculating the mean response for each MOE. From Appendix D it can be seen that to use the means raised the explanatory power of the model with only main effects already to 78–87% of the variability.

For the MOE "BLUE casualties" it is unclear why the BLUE casualties would rise when the "TOW" range is increased. As no error in the model could be found the author decided to conduct 1000 additional replications of the simulation in which only the TOW range varied. The result is that the TOW range has nearly no effect on the BLUE casualty level, which only showed a slight decrease. It would seem that especially for weak relationships between MOEs and factors, random effects can cause a small *type I* error. This means that a factor can be added through random effects—even with the wrong sign—to a regression model when there is no significant relationship. When more replications are done, errors happen less often, but absolute certainty cannot be achieved.

On the other hand, for the MOEs where TOW range is a more important factor (as it is for “RED casualties” or “CGV casualties”) it can be seen that the sign of the factor and its influence is logical and in the right direction. To take this into account only the most important and influential factors are considered in the following regression models.

c. Most Important Main Effects

Number of BLUE infantry carried: The most important contributing factor for BLUE casualties is the number of BLUE infantry brought to the battle. It is counterintuitive that a higher number of available infantry raises the number of overall BLUE casualties. Responsible for the effect is the scenario itself. As the RED forces have a high quantity of indirect fire available and can use their long range anti-tank weapons on infantry, more BLUE infantry means that the RED agents have a greater number of vulnerable targets. Of course, the number of RED casualties increases with more BLUE infantry available, so the effect on the casualty ratio is not as strong as it is for BLUE casualties. Overall, this factor is considered heavily scenario dependent.

Detection of vehicles and infantry for the GCV: The most significant factors for decreasing BLUE casualties are better sensors on the GCV. Better sensors enable the GCVs to detect, report, and engage the enemy faster and to increase the situational awareness of all BLUE agents. Therefore, the sensor quality is also one of the most influential factors for decreasing the battle duration. Considering only RED casualties, the ability to detect infantry clearly dominates the vehicle sensor effects as most of the RED agents are infantry soldiers. Surprisingly, better sensors do not have much influence on the survivability of the GCV itself. Here, other factors dominate the model. The reason for this is that the basic sensor is already good enough for self-protection, but not for providing covering fire for other units as this requires longer distance detections.

Concealment: One important battle parameter is the ability of the GCV to hide. As expected, it decreases the GCV casualty expectance. The marked decrease in overall BLUE casualty expectance shows how important the combined action of infantry carrier and supported infantry proves in the scenario. Similarly, casualties of the infantry decrease drastically with better survivability of the GCV and so does the BLUE casualty ratio. Interestingly, concealment has the most influence on battle duration. The reason for this is that the BLUE forces are able to avoid detection by RED and therefore can reach the objective without having to destroy every RED battle position. Notice that this is the reason why the RED casualty expectance decreases with a higher concealment rate.

Mortar: Another important contributor for improving the GCV performance for all considered MOEs is the addition of an advanced indirect fire capacity. Area fire without delay proves to be the most important main effect for RED casualties and for the casualty ratio. With this additional firepower BLUE casualties can be avoided and the battle duration decreased.

Number of hits for the GCV: As the model shows, the “robustness” of a GCV against enemy fire is most important as it is unavoidable that the GCVs get hit. As the GCV make up only a small part of the overall BLUE force, the influence on the total BLUE casualties and the casualty ratio is not significant. For the survivability of the GCV this is the most contributing factor.

Active defense measures: Notice that this factor is modeled as reduced anti-tank kill probability. This means a higher value decreases the active defense effectiveness, and the model parameter must be multiplied by minus one. Active defense measures have effects similar to the number of hits. Therefore, it can be modeled as a combined factor in future studies.

TOW: In the scenario, long-range weapon capabilities prove to be important. For the CGV, the survivability is dependent on the range advantage against enemy infantry, and therefore, the TOW helps to increase enemy casualties and reduced casualties on the GCV side.

All other factors are not as important. Notice that the "BLUE casualties," "RED casualties," the "casualty ratio" and the "battle duration" can be considered as MOEs for the system of systems (that is, the whole BLUE force), while the "GCV casualty" MOE is different as it directly measures the survivability of the GCV. Here, factors like armor and speed of the GCVs are important while they are not for the other MOEs.

5. Insights

The conclusion from the R-square value analysis is that it is impossible to predict the outcome of a battle even when all factors are known. The variance caused by agent interactions and the influence of randomness are much greater than superior numbers or better specification parameters of the GCV. As the behavior of the agents' shows great similarity to actual human behavior, it is a major insight that even with the best knowledge of the enemy and our own forces (including intangibles such as leadership) a battle outcome cannot be predicted for sure. Instead, as the "mean" regression model showed, it is possible to determine the odds of a battle. The approach historians typically take to look at a single battle and find the factors for victory and failure can therefore be doubted.

Additionally, the following conclusions can be drawn from the analysis:

- The used tactic of dismount immediately when under fire or spot the enemy greatly increased the expected casualty rate, if the enemy had a sufficient amount and accuracy of indirect fire.
- Improved sensor quality of one system combined with network capabilities can greatly enhance the performance of the whole force according to casualty expectance and battle duration.
- Advanced concealment technologies promise to be able to avoid ambushes and could enable our own forces to take objectives in much less time with fewer casualties. It can also prove useful for improving convoy security while conducting logistics operations.
- Against infantry in prepared positions, indirect, organic fire capability is a great advantage.
- Even with the best armor, the best defense system, and the best tactics, it is unavoidable that sometimes the enemy hits a GCV in a

vulnerable location. The "robustness" of a GCV is important to minimize losses and improve mission performance.

- System of systems MOEs behave differently than the directly measured MOE for just one system like the GCV.

As the estimation of the factors for the MOE does not change by using the MOE means as dependent variables, all other analysis is done by using the mean data.

6. Partition Trees

Partition trees are a different tool for analyzing the most influential factors. Here, the factor as a whole is not considered, but the algorithm tries to split the factors at a certain value so that the most variance can be explained by this division, and the errors are reduced. The advantage of this approach is that it allows for finding critical values for designing a weapon system.

a. "BLUE Casualty" Partition Tree

In Figure 27, it can be seen that if the sensor for vehicles can be improved to 150% effectiveness the BLUE casualty expectance goes down from 23 agents killed to only 20 per battle (a 15% reduction). Another critical threshold value is to improve the sensor at least to 120% effectiveness. The tree diagram gives also the most influential factors according to the split sequence. The percentage of explained variance with each splitting can be seen in Figure 28. As the increase of the curve flattens out after six splits only these six are considered.

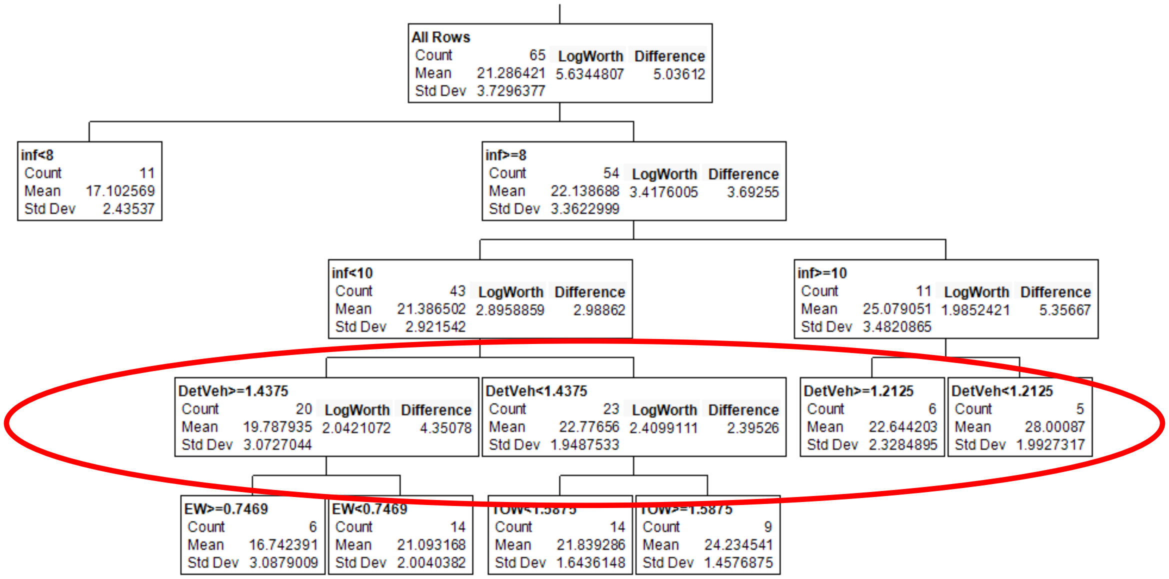


Figure 27. Partition tree for BLUE casualties.

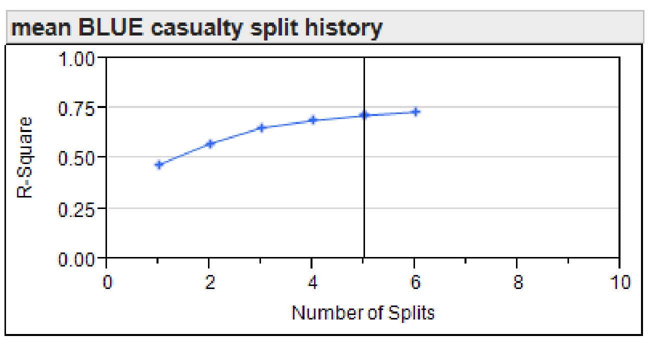


Figure 28. History of split for BLUE casualties; the black vertical line shows the number of used splits.

Graphs and statistics for the other MOEs can be found in Appendix D.

b. Most Important Main Effects

In comparison with the most important factors from the main effects models a high correlation can be observed with the partition tree models. The two (in most cases three) most influential factors are the same. Therefore, the results in the previous chapter are confirmed. Conclusions from the partition trees are sorted according to MOEs.

BLUE casualties: The result for the two most influential factors, “number of infantry carried” and “sensor for vehicles,” match up with the main effects model. As stated before, two critical threshold values can be identified for the effectiveness of the sensor. An additional insight is that the importance of the long-range TOW and the importance of the EW depend on the sensor quality for vehicles. It is logical that a better long-range weapon system is only effective when the according sensor has the same range. If this is not the case, for example due weather conditions, other factors like EW can be more efficient in reducing casualties.

RED casualties: For this MOE the three most important factors, “mortar,” “detection of infantry” and “number of hits,” matches up with the main effects model. Depending on whether an indirect fire weapon is added to the GCV there can be two threshold values identified for the infantry sensors. This result emphasizes again the correlation between weapon system range and corresponding sensor.

Casualty ratio: For the casualty ratio both tools give as the most important factors the “indirect fire weapon,” the “infantry sensor effectiveness” and the GCV “concealment.” Regardless of whether the indirect fire weapon is installed on the GCVs there is a threshold level for the “infantry sensor,” but depending on the existence of the weapon both thresholds differ.

Battle duration: As the three most influential factors match up again (“concealment,” “sensor effectiveness for vehicles,” “indirect fire weapon”) the previous result could be confirmed. Times to reach an objective in the scenario are highly correlated to the ability of avoiding contact with the enemy and the survivability of the GCVs.

GCV casualties: Again, the three most influential factors (“number of hits,” “active defense,” “armor”) are confirmed. An additional insight is that if the GCV is not robust (= can take only one hit) “armor thickness” is the second most influential factor. If, by contrast, the vehicle can take more hits on average, “active defense” means become more relevant.

7. Interaction Regression Models

The next step in the analysis is to consider the effects of interactions between the main effects and non-linear dependencies. The problem here is the limited number of “degrees of freedoms” (DF) in the used DOE. The 65 design points translated to 63 DF since two are used for estimating mean and error.

Pre-analysis shows that linear effects are mostly sufficient, but quadratic effects should be considered, as shown in Table 11.

Table 11. Non-linear effects: An “X” indicates that the factor is considered with quadratic effects for the corresponding MOE.

	conceal	speed	armor	#inf	Detinf	DetVeh	Bush	MG	TOW	CW	EW	AD
BLUE cas	X				X							
RED cas	X		X		X					X	X	
Cas ratio	X											X
Battle time	X											X
GCV cas			X								X	X

The pre-analysis also shows that interaction terms are highly influential and must be considered. Due to the limited number of DF, the following models take into consideration the seven most influential main effects up to three-way interactions, which uses the maximum of 63 DF.

The general sequence for finding the advanced regression model is as follows:

- Use the main effects and the squares.
- Use main effects, significant square terms, and two-way interactions.
- Use main effects, significant square terms and two/three-way interactions on a reduced number of main factors (usually the seven most influential main effects).
- Compare and find the "best" models according to the R^2 and R^2_{adj} values.

In the selection process, the number of factors in the model is tried to be reduced as the purpose is to find the most influential factors. Therefore, if a model has only slightly higher R^2 and R^2_{adj} values by adding an additional factor, the factor is left out. Furthermore, the threshold for explained variance has been chosen to be 80% or above. If interactions or quadratic terms become part of the model the author chose to leave the corresponding main effects also in the model as it keeps the model hierarchical.

For the MOE "BLUE casualties" the model is explained in the following section. An "Actual by Predicted Plot" is shown in Figure 29. This plot gives a visual impression of how close the MOE value can be predicted by the model.

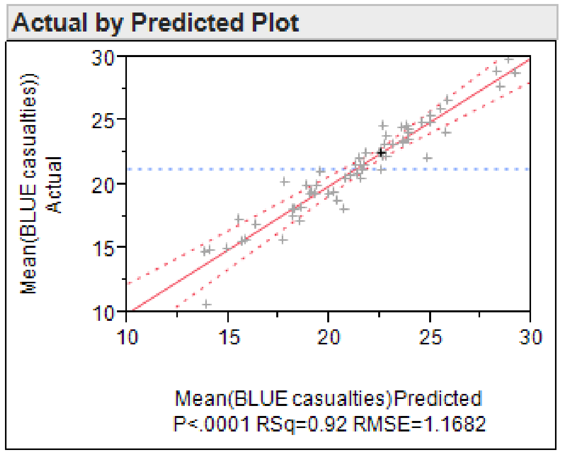


Figure 29. Predicted mean of the BLUE casualties (RED line) against the observed means (gray crosses). The dotted BLUE line shows the overall mean of the BLUE casualties for the total 29900 runs.

The model fits the observed means very well as can be seen in Figure 30. There are no outliers, and the model has a high predictive power in the observed range. Notice that the examined factor ranges are chosen according to the maximum possible values in reality, which means that the results are valid for any kind of GCV development in the next decade.

Summary of Fit

RSquare	0.921816
RSquare Adj	0.901887
Root Mean Square Error	1.168235
Mean of Response	21.28642
Observations (or Sum Wgts)	65

Figure 30. Summary fit of the “BLUE casualties” model; the $\boldsymbol{R^2}$ shows that 92 % of the variance is explained by the fitted meta-model and the corresponding $\boldsymbol{R^2_{adj}}$ value shows that only important factors are included as the difference between them is small.

The advanced regression model with all its factors displayed in the sequence of their importance is shown in Figure 31.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
inf	2.0773791	0.153438	13.54	<.0001*
DetVeh	-4.217257	0.417188	-10.11	<.0001*
DetInf	-4.106216	0.42068	-9.76	<.0001*
conceal	-0.030726	0.005095	-6.03	<.0001*
(conceal-50.0154)*(conceal-50.0154)	-0.001164	0.000216	-5.40	<.0001*
Mortar[0]	0.7887828	0.147811	5.34	<.0001*
EW	-2.108198	0.551406	-3.82	0.0004*
TOW	1.2893396	0.414926	3.11	0.0031*
(conceal-50.0154)*(TOW-1.40002)*(EW-0.55001)	0.1351961	0.044183	3.06	0.0035*
(conceal-50.0154)*(EW-0.55001)	-0.055048	0.018571	-2.96	0.0046*
(conceal-50.0154)*(DetInf-1.40002)	-0.046325	0.018418	-2.52	0.0151*
(TOW-1.40002)*(EW-0.55001)	2.8375366	1.445128	1.96	0.0550
(conceal-50.0154)*(TOW-1.40002)	-0.006264	0.013291	-0.47	0.6394

Figure 31. Model parameter estimates of the “BLUE casualties.”

Another useful analysis tool is the prediction profiler. The prediction profiler illustrates the variability of the MOE according to changes in the main effects as shown in Figure 32. If the bend of the BLUE curve or the angle of BLUE lines is high then the MOE values react sensitively to changes in the corresponding main effect.

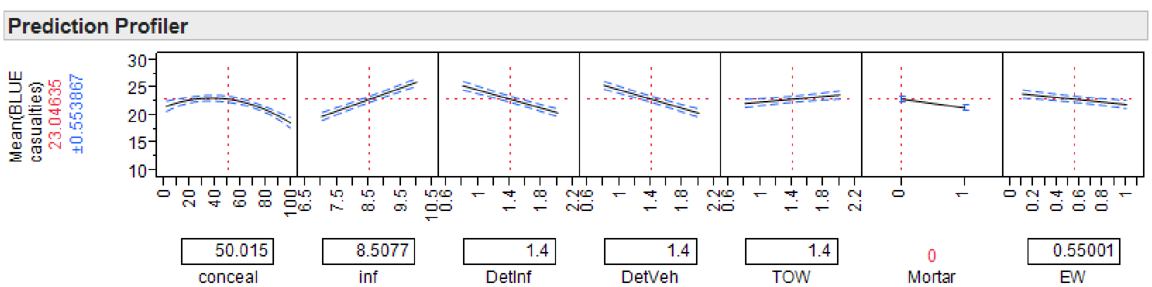


Figure 32. Prediction profiler. Shown are the seven main effects used in the previous model. The x-axis shows the value of each main effect and the y-axis the value of the mean BLUE casualties. The blue line represents the actual change of the MOE with the corresponding main effect. The dotted lines giving a 95% confidence interval. Red dotted lines represent the overall mean values of the MOE and the corresponding effects.

Figure 32 shows additionally that the main effect has not changed in comparison with the previous models. The result of the pre-analysis is confirmed as the model shows the quadratic relation between MOE and concealment is highly significant. It also can be seen that interactions are included in the model.

The advanced model explains 92% of the variance in contrast to the 85% for the main effects model and increases $\boldsymbol{R^2_{adj}}$ from 0.8 to 0.9 while reducing the included number of terms from 14 to 13.

The number of terms to be included can be chosen freely. More terms always increase the R^2value. So a “Pareto Plot” such as the one shown in Figure 33 and the $\boldsymbol{R^2_{adj}}$values are used to restrict the number of terms to only the most influential ones. Note that after the TOW main effect, the curve in Figure 33 flattens out, so no additional terms are added to the model.

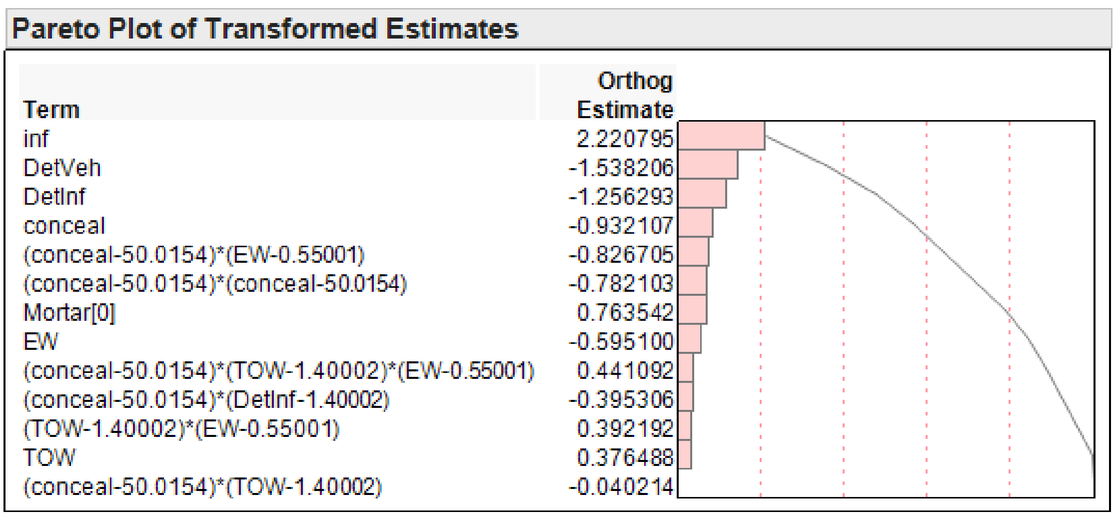


Figure 33. Pareto plot showing (blue line) how much additional variance can be explained by adding a new factor.

8. Insights

Interactions (even three-way) matter and therefore *must* be considered in the specification process. Even when there are more important main effects the overall performance of a GCV is also dependent on interactions. Whenever a system is tested, these interactions must be quantified as part of the vehicle evaluation and taken into consideration when changes are applied.

Of particular significance is the factor of concealment. Concealment of the GCV changes the MOE with a non-linear, probably quadratic, relationship. This factor is especially useful in the scenario to reduce casualties when applied in combination with electronic warfare and long-range weapon systems. The reason for this combination is that single enemy agents can detect the concealed GCV for short time periods. When this agent is not able to provide the information to his allies no coordinated action can be taken against the GCV, and the concealed CGV is able to destroy or evade other RED agents still not aware that the GCV is in range. Therefore, the effect of concealment is multiplied.

The advanced regression models for the other MOEs are given in Appendix E, and only an overview of the results is represented in Table 12.

Table 12. Overview of advanced regression models for infantry carrier GCV. A confirmation of the main effects result is considered when the sequence of the main effects has not changed. Corresponding $\boldsymbol{R^2}$ and $\boldsymbol{R^2_{adj}}$values from the main effects regression model are shown.

	$\boldsymbol{R^2}$	$\boldsymbol{R^2_{adj}}$	**# of terms**	**Main effect result confirmed**	**Main effect $\boldsymbol{R^2}$**	**Main effect $\boldsymbol{R^2_{adj}}$**
RED Cas	0.94	0.93	13	Yes	0.86	0.82
Cas ratio	0.84	0.80	13	Yes	0.77	0.71
Battle time	0.82	0.78	10	No	0.78	0.70
GCV cas	0.96	0.95	13	Yes	0.82	0.76

Several findings emerge from the advanced regression models. In the case of “RED casualties,” “casualty ratio,” and “Battle time” (duration), concealment has a quadratic relationship to the MOE.

“RED casualties”

- Concealment has again a quadratic relationship with the MOE.
- The robustness of the GCV interacts with the longer range of the main “TOW” weapon and is one of the most influential factors to increase RED casualties. This interaction is more important than “TOW” range alone and shows the importance of interaction between survivability and lethality for inflicting damage to the enemy.

“Casualty ratio”

- “Concealment” has again a quadratic relationship with the MOE.
- “Concealment” appears in most relevant interactions. It is more important in interactions with “EW,” “Mortar,” and “active defense.” This means that the effect of “concealment” on the casualty ratio can be increased if the own force survivability and lethality is higher and the enemy communication abilities are decreased. This result also confirms the previous found relationship between “concealment” and “EW.”

“Battle time”

- “Concealment” has a quadratic relationship with the MOE
- The sequence for the main effect is not the same as in the pure main effect model. Now “mortar” and “detection of infantry” have increased influence, while the influence of “concealment” decreased. The “number of GCV hits” is no longer relevant.
    - “Concealment” shows again importance of interactions with “mortar,” “EW” and “active defense.”

“GCV casualties”

- The most influential factors for the survivability of the GCV are confirmed with “robustness of a vehicle,” the “quality of the active defense,” and its “armor.” Also, the lethality against anti-tank weapons increases its survivability. The regression model shows that the entire main “survivability factors” mentioned above have important interactions among each other.

9. Conclusions

Among the conclusions drawn in regard to the models are the following:

- All models are checked if they have any outliers in their prediction. Only for the “Battle duration” MOE can one outlier be identified, which gives the author a high confidence in the correctness of the regression models in catching the interdependencies of the conducted combat simulation.
- All final regression models have greater explanatory power than the main effect counterparts with fewer factors included as can be seen in Table 12. Therefore, interactions and non-linearities matter and must be addressed in the specification process.
- All advanced regression models confirm the sequence of the main effects in order of their importance besides the “Battle duration” model. Here, the order changed slightly but still confirmed the basic insights.

10. Robust Solution

The last step is to find a robust solution for the specification parameters for the GCV.

No simulation can exactly predict the future and even the best underlying scenarios for specifications will not look like the environment the GCV will face in the real world. Therefore, the predicted performance for the found influential factors will also not match up with the real performance. To take this into account, a tradeoff between overall performance and the variability of the result must be made. Notice that the variance for the MOEs can also be called “uncertainty of the MOE.” This means that the regression model of the variance can be used to see what factors contribute most to the uncertainty of the MOE.

To come up with a robust solution for specifications the decision maker must define how he or she wants to weigh the different MOEs and how to weigh the likelihood of all underlying scenarios. If there are three different scenarios the most influential factors will differ from scenario to scenario. While in a conventional war scenario “speed” can be influential this must not be the case if the scenario deploys the GCVs on fixed check points.

For the purpose of this study the process is shown for one scenario and the MOE “GCV casualties.” This choice is made because for a specification process MOEs measuring direct performance are easier to understand than indirect MOEs.

The found regression model equation for “GCV casualties” is

“GCV casualties” = *0.9233 - 0.4125 * “3hits” + 0.6334 * “actDef” - 0.7409 * “3hits” * “actDef” - 0.0005 * “armor” + 0.3637 * “3hits” * “TOW” - 0.2660* “TOW” + 0.0004 * ”3hits” * “armor” - 0.9130 * “TOW” * “actDef” + 1.4748 * “hits” * “TOW” * “actDef” - 0.0017 * “conceal” - 0.0566*"2hits"- 0.0010* "conceal" * "mortar" + 0.0240 * "No mortar"*

The regression model for the variance of the MOE “GCV casualties” is

Variance (“GCV casualties”) = *0.9399 - 0.3957 * “3hits” - 0.0007 * “armor” + 0.5937 * “actDef” - 0.3324 * “TOW” + 0.0004 * “3hits”*”armor” - 0.2880 * “3hits” * “actDef” - 0.0019 * “conceal” + 0.2151 * “3hits” * “TOW” - 0.0643 * “2hits” + 0.049 * “No mortar” - 0.4318 * “TOW” * “actDef” * 0.0063 * “speed”*

Now both must be combined by a so-called “loss-function.” The idea is that a higher performance with a higher variance might not be as desirable as a slightly lower performance with a lower variance. Lower variance means that the result will be more stable. The combined loss-function can be chosen according to the practical problem. Here, there is no loss associated with fewer casualties. Therefore, loss will only occur when the casualties are higher and a one sided loss-function is appropriate. How this loss-function is chosen depends on the situation and on the preference of the analyst (P. Sanchez, 2010).

11. Results

The author followed the outlined approach and found that with a higher performance the variance is decreasing. There is nearly a perfect, positive correlation between variance and the MOE as shown in Figure 34.

Correlation between GCV Variance and GCV Casualty MOE

Correlations

	Mean(GCV_cas)	Variance(GCV_cas)
Mean(GCV_cas)	1.0000	0.9837
Variance(GCV_cas)	0.9837	1.0000

Scatterplot Matrix

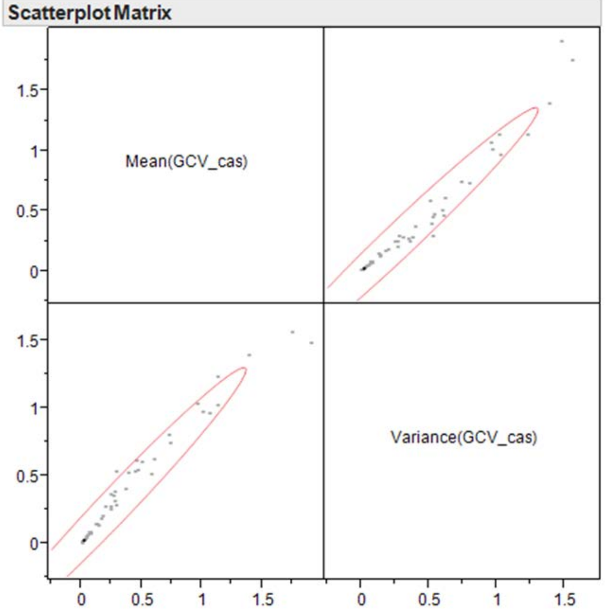


Figure 34. Correlation between GCV variance and casualty GCV MOE. Note that the scatterplot shows that when the casualty rate of the GCVs increases the variance also increases. A perfect correlation would have the value of 1 and would be represented as a bisecting line in the first quadrant.

The consequence is that no loss function is needed. Whenever the performance is higher, the variance decreases. If this is the case for all combat simulations, it is beyond the scope of the thesis; but it emphasizes the result found by Hillestad that the variance of the combat simulation results decreases if the setup increasingly departs from a draw situation (Hillestad, Owen, & Blumenthal, 1995). A closer analysis of the factors shows that this is especially true for the number of hits the GCV has, which has been determined before as the most influential factor for the variance. The graph in Figure 35 shows how not only the mean of the expected casualty rate for GCV decreases, but also the variance decreases.

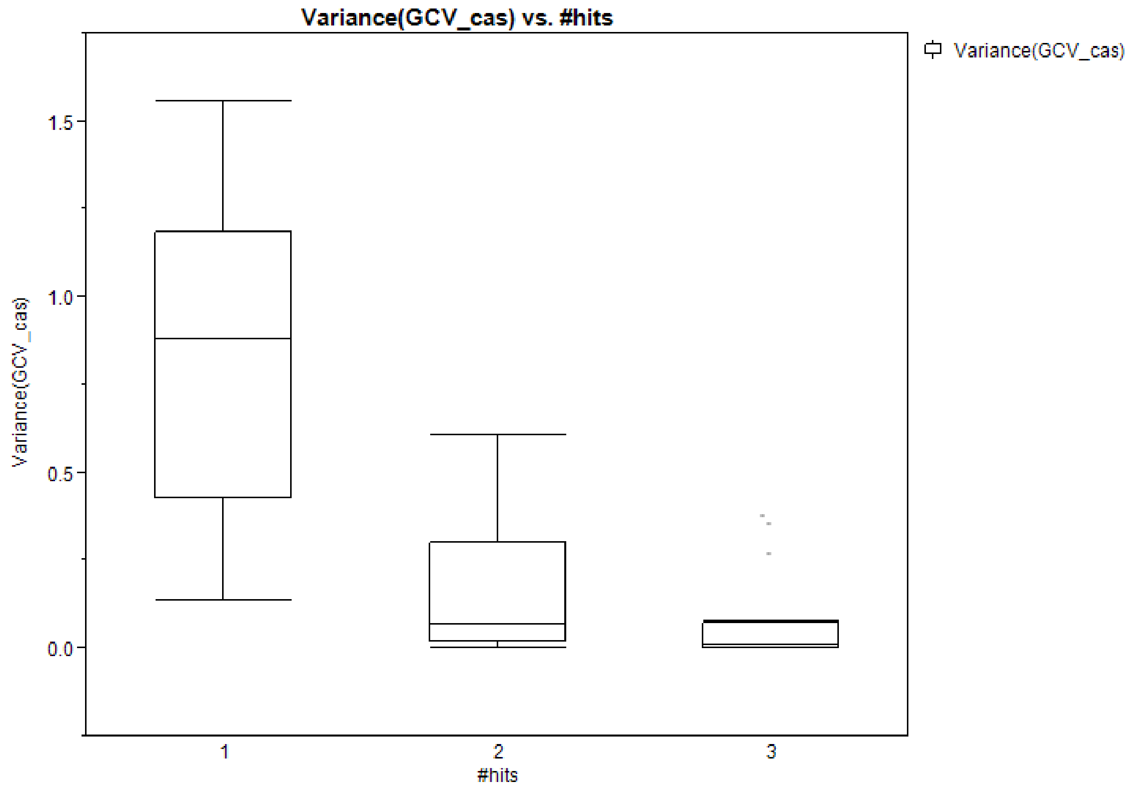


Figure 35. Impact of GCV hits on variance. The x-axis shows the three levels of hits the GCV has. The box-plot whiskers show how variable the solution is and the horizontal line gives the mean of the GCV casualties.

To sum it up, the better the performance of the GCVs, the more "robust" the solution is. This result helps for the future work on the engineering side of the specification process as the engineers need only address the performance MOE as this automatically reduces the variance. This finding also simplifies the implementation of the thesis results in the "dashboard."

C. ANALYSIS CGV: MAIN BATTLE TANKS

As in the previous chapter, the same analysis is done when substituting the Abrams main battle tank platoon into the scenario. There are two reasons for this analysis method:

- First, the additional analysis is needed to see if the used analysis approach holds for different situations and to gain additional insights.
- Second, the German government plans to build a new main battle tank, and the author plans to use this data and approach for the concept development of this new "tank GCV."

1. Correlation of the MOEs

From the chosen MOE a correlation matrix is calculated to see if some MOEs can be combined. As the GCVs carry no infantry, the "infantry casualty" MOE is not considered. For the remaining six MOEs the result is shown in Table 13. The threshold for high correlation is set again to 0.7, where red text indicates high correlation. Therefore, the MOE for "BLUE victories" and "casualty ratio" are combined this time within the MOE "BLUE casualties," and "Sqd7 Cas" represents the casualties of the GCVs.

Table 13. Correlation table. The table shows the correlation between the six MOEs. The RED color shows high correlation. "Sqd7 Cas" represents the casualties of the GCVs

Correlations

	Mean(Alleg1Cas(Blue))	Mean(Alleg2Cas(Red))	Mean(Steps)	Mean(Casualty ratio)	Mean(win)	Mean(Sqd7Cas)
Mean(Alleg1Cas(Blue))	1.0000	-0.6803	-0.0252	-0.9408	-0.8967	0.4848
Mean(Alleg2Cas(Red))	-0.6803	1.0000	0.4304	0.6204	0.7028	-0.3406
Mean(Steps)	-0.0252	0.4304	1.0000	-0.0873	0.2042	0.1206
Mean(Casualty ratio)	-0.9408	0.6204	-0.0873	1.0000	0.7154	-0.4243
Mean(win)	-0.8967	0.7028	0.2042	0.7154	1.0000	-0.4836
Mean(Sqd7Cas)	0.4848	-0.3406	0.1206	-0.4243	-0.4836	1.0000

2. Factor Screening

The following sections examine the major contributing factors for the four remaining MOEs and will explore the interactions and non-linear effects contributing to these MOEs. The number of included factors in the resulting meta-models is minimized for better practical and explanatory usage.

a. Main Effect Model

The main effect models are found with the same approach as before. The results are displayed in Figure 34–Figure 37. Additional graphs are provided in Appendix G.

BLUE casualties

Summary of Fit

RSquare	0.920771
RSquare Adj	0.900575
Root Mean Square Error	0.9135
Mean of Response	12.73311
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	12.737717	0.119038	107.01	<.0001*
actDef	3.5640104	0.193717	18.40	<.0001*
Mortar[0]	1.3392454	0.115425	11.60	<.0001*
Mortar[1]	-1.339245	0.115425	-11.60	<.0001*
DetVeh	-1.60646	0.193769	-8.29	<.0001*
#hits[3]	-0.42297	0.177154	-2.39	0.0207*
armor	-0.373124	0.193716	-1.93	0.0597
#hits[1]	0.331545	0.181777	1.82	0.0740
speed	-0.348571	0.19274	-1.81	0.0764
CentricW	-0.349254	0.193775	-1.80	0.0774
120mm	0.2857365	0.196426	1.45	0.1519
conceal	-0.251783	0.193725	-1.30	0.1996
DetInf	-0.158796	0.194254	-0.82	0.4175
#hits[2]	0.0914246	0.152461	0.60	0.5514
MG	-0.111972	0.193553	-0.58	0.5655
EW	0.068666	0.195181	0.35	0.7264

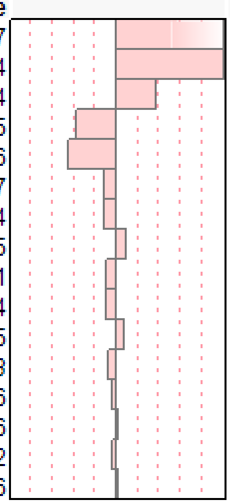


Figure 36. Main effect regression model for “BLUE casualties.”

RED casualties

Summary of Fit

RSquare	0.891802
RSquare Adj	0.864222
Root Mean Square Error	0.484
Mean of Response	63.91508
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	63.863286	0.06307	1012.58	<.0001*
Mortar[0]	-0.799088	0.061156	-13.07	<.0001*
Mortar[1]	0.7990876	0.061156	13.07	<.0001*
actDef	-1.012418	0.102637	-9.86	<.0001*
conceal	-0.777633	0.102641	-7.58	<.0001*
DetInf	0.6858084	0.102922	6.66	<.0001*
#hits[1]	-0.356416	0.096311	-3.70	0.0005*
#hits[3]	0.208992	0.093861	2.23	0.0304*
#hits[2]	0.1474244	0.080778	1.83	0.0739
armor	0.1821722	0.102637	1.77	0.0819
EW	-0.128216	0.103413	-1.24	0.2207
speed	0.1020397	0.102119	1.00	0.3224
120mm	0.0863174	0.104072	0.83	0.4107
DetVeh	-0.079737	0.102665	-0.78	0.4409
CentricW	-0.045806	0.102668	-0.45	0.6574
MG	-0.021798	0.10255	-0.21	0.8325

Figure 37. Main effect regression model for “RED casualties.”

Battle duration

Summary of Fit

RSquare	0.875733
RSquare Adj	0.844057
Root Mean Square Error	719.0304
Mean of Response	16212.39
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	16216.499	93.69655	173.07	<.0001*
conceal	-1853.783	152.4841	-12.16	<.0001*
DetInf	1351.8574	152.9006	8.84	<.0001*
actDef	-1228.939	152.4777	-8.06	<.0001*
DetVeh	-814.6284	152.5188	-5.34	<.0001*
Mortar[0]	375.84259	90.85291	4.14	0.0001*
Mortar[1]	-375.8426	90.85291	-4.14	0.0001*
CentricW	-501.1171	152.5233	-3.29	0.0018*
speed	-410.6871	151.7085	-2.71	0.0092*
120mm	314.7322	154.6099	2.04	0.0470*
MG	-153.0135	152.3489	-1.00	0.3199
EW	-116.5329	153.6304	-0.76	0.4516
armor	-10.95701	152.477	-0.07	0.9430
#hits[3]	-9.637628	139.4405	-0.07	0.9452
#hits[2]	7.3864169	120.0046	0.06	0.9512
#hits[1]	2.2512116	143.0795	0.02	0.9875

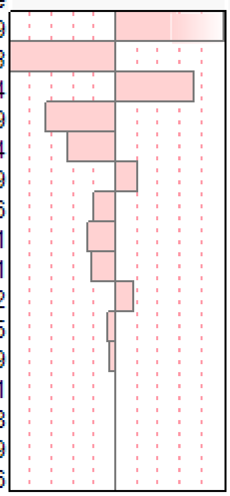


Figure 38. Main effect regression model for “Battle duration.”

GCV casualties

Summary of Fit

RSquare	0.738253
RSquare Adj	0.671533
Root Mean Square Error	0.207483
Mean of Response	0.234759
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.2696476	0.027037	9.97	<.0001*
#hits[1]	0.3400223	0.041287	8.24	<.0001*
armor	-0.284072	0.043999	-6.46	<.0001*
#hits[3]	-0.214142	0.040237	-5.32	<.0001*
actDef	0.1919046	0.043999	4.36	<.0001*
#hits[2]	-0.12588	0.034628	-3.64	0.0006*
conceal	-0.079515	0.044001	-1.81	0.0766
Mortar[0]	0.0395337	0.026216	1.51	0.1377
Mortar[1]	-0.039534	0.026216	-1.51	0.1377
DetVeh	-0.050965	0.044011	-1.16	0.2522
EW	-0.030936	0.044331	-0.70	0.4885
DetInf	-0.028131	0.044121	-0.64	0.5266
120mm	0.0144403	0.044614	0.32	0.7475
CentricW	0.0124164	0.044012	0.28	0.7790
speed	0.0100765	0.043777	0.23	0.8189
MG	-0.000747	0.043962	-0.02	0.9865

Figure 39. Main effect regression model for “CGV casualties.”

b. Most important Main Effects

Active defense measures: The overall most influential factor for the four MOEs is “actDef.” It contributes to each MOE significantly. Good active defensive systems increase the survivability of the GCV. As the tank GCV has a high lethality its higher survivability enables it to kill more enemy agents and to draw more enemy fire; so, the overall “BLUE casualties” are reduced, and the number of “RED casualties” increases. With a greater advantage for the BLUE forces the battle duration is reduced. The author found the same relationships for the survivability factors “hits” and “armor.”

Concealment: As they were for the infantry carrier, concealment measures are a major contributor to overall battlefield performance. BLUE “CGV casualties” and “BLUE overall casualties” are slightly reduced. Interestingly, a higher concealment rate also reduced the number of “RED casualties” and the “battle duration” significantly. The reason for this effect is again that the BLUE CGV is able to avoid contact and therefore leaves enemy agents behind while reaching its objective faster. So the previous observation for the infantry carrier is confirmed.

Detection of vehicles and infantry for the GCV: Again, a better sensor system has an important effect on the performance of the GCV, but it is much less significant than it was for the infantry carrier CGV. In general the findings for the infantry carrier can be confirmed; but as the tank already has better sensors in comparison to the infantry carrier, the increase in the ranges and the probabilities of detection are not as important.

Mortar: The addition of an organic indirect fire is again the most significant contributing factor for “RED casualties.” It also influences “battle duration” and “BLUE casualties” significantly. The previous results for the infantry carrier can be confirmed.

3. Insights

In general, the author finds that the same factors contribute to the survivability of an infantry carrier GCV as they do for a main battle tank GCV. However, the importance of specific factors differs. Therefore, additional studies can be done to see if performance parameters are scenario dependent or whether they depend more on the purpose of the vehicle in the scenario. If the parameters are mostly scenario dependent, the chosen “most-likely” scenarios would already define most of the important performance factors. Notice that the “number of infantry carried” is an important factor for an infantry carrying GCV, but this factor is not applicable at all for a battle tank. In addition the infantry-carrier GCV improvements in the long-range weapons matter, while improvements to the “120mm” gun of the tank GCV do not because the tank already has superior firepower.

Additionally, the author arrived at the following insights:

- In a comparison of the infantry carrier and the battle tank GCV it can be shown that the significance of the improvement of a factor is dependent on its previous level of importance. For example, it might not be cost efficient to increase the performance of an already excellent detection system. To improve or eliminate known weaknesses of the previous system class vehicles is more important. So the “Pareto principle” applies in the specification process of the GCV, and non-linear effects must be covered as well in an analysis.
- Major performance parameters are dependent on the scenario and the purpose of the vehicle. Therefore, they are similar for different GCV classes.

4. Partition Tree Analysis

Graphics and statistics related to the partition tree analysis discussed in this section can be found in Appendix H.

The partition tree analysis confirms the main effect results.

“BLUE casualties:” The model shows that influential factors such as “mortar” are strongly dependent on the value of the active defense. If a strong active defense is installed, the GCV significantly increases the BLUE force survivability by improving vehicle sensors and adding an indirect fire weapon.

“RED casualties:” The partition tree indicates that depending on whether an indirect fire weapon is installed, the influence of an active defense system and the camouflage ability of the GCV varies. If the GCV has an indirect fire weapon and is able to move within range of the RED infantry, the number of “RED casualties” is significantly increased. Otherwise, protection against long-range anti-tank weapon systems becomes more important, and the fight is conducted at longer ranges.

“GCV casualties:” Here, the influence of the most straightforward factors (that is, “number of hits,” “armor” and “actDef”) is confirmed as the most significant for survivability. The partition tree model shows that, depending on the robustness of a vehicle, different thresholds for armor thickness can be considered to improve the vehicle’s performance and that the best protection results from a mix of armor and robust design.

5. Interaction Regression Models

To find influential quadratic effects a pre-analysis is conducted on the main effects. The results are given in Table 14.

Table 14. Result of pre-analysis scanning for quadratic relationships between MOEs and main effects

	conceal	speed	armor	#inf	Detinf	DetVeh	Bush	MG	TOW	CW	EW	AD
BLUE cas		X										
RED cas	X	X										
Battle time	X				X	X						X
GCV cas	X										X	

For the advanced regression models non-linear factors, together with the seven most influential main effects, up to their three-way interactions are considered. The regression models are shown in Appendix I, and the main statistics are given in Table 15. Notice that each model has been able to achieve a higher explanatory power than the 13 factor main effects model and with fewer factors. So, the importance of the non-linear effects and their interactions is confirmed. Furthermore, the non-linear regression model predicted the mean MOE outcomes very well. Only the “battle duration” MOE shows one outlier.

Table 15. Overview of the final regression models for the “tank” GCV. A confirmation of the main effect result is considered when the sequence of the main affects has not changed. The last two columns show the corresponding $\boldsymbol{R^2}$ and $\boldsymbol{R^2_{adj}}$ values from the main effects regression model.

	$\boldsymbol{R^2}$	$\boldsymbol{R^2_{adj}}$	**# of parameter**	**Main effect result confirmed**	**Main effect $\boldsymbol{R^2}$**	**Main effect $\boldsymbol{R^2_{adj}}$**
BLUE Cas	0.93	0.92	8	Yes	0.92	0.90
RED Cas	0.90	0.89	8	Yes	0.89	0.86
Battle duration	0.92	0.91	11	Yes	0.88	0.84
GCV cas	0.85	0.84	7	Yes	0.74	0.67

6. Insights

a. “BLUE Casualties”

- The regression confirmed the results from the main effects model. It also showed that the performance of an additional indirect fire weapon depends on the effectiveness of the active defense systems of the GCV. If the survivability rate of the GCV is higher at close ranges the GCV can get into effective mortar range to engage the enemy. If the enemy anti-tank weapons are effective, “tank” GCV should use their range advantage with their main gun to destroy the enemy at long ranges to reduce GCV casualties.

b. “RED Casualties”

- As shown in the pre-analysis, the influence of concealment on the MOE is quadratic.
- The dependency of the indirect fire weapon performance on the quality of the active defense systems can be shown again. Therefore, not only is the BLUE force casualty rate reduced from a combination of indirect fire and active defense system, but also the number of RED agents killed is increased.

c. “Battle Duration”

- The pre-analysis result for the non-linear effect on the MOE for “concealment” and “DetInf” is confirmed.
- A dependency between the concealment ability and the sensor quality can be deduced from the regression model. This relationship emphasizes the importance of superior situation awareness as the GCVs are able to detect the enemy without being seen themselves. Therefore, the GCVs are able to destroy the enemy while maintaining a high survivability rate themselves or to avoid contact with the enemy entirely and reach the mission goal earlier.

d. “GCV Casualties”

- The model gives the expected result that the main components of survivability are “robustness,” “armor” and “actDef.” The additional consideration is that there are interactions between all these factors so that none of these can be considered separately.

7. Summary

- All non-linear models kept the sequence of the main effects models and the partition trees. This fact shows that the meta-models are stable and indicates that the found influential factors are correct.
- The results emphasize the importance of non-linear and interaction effects which must be studied to develop an optimal specification set.

8. Robust Solution

The analysis of the robust solution follows the same steps used for the infantry GCV. As the study showed before, the variance of the MOE “CGV casualties” is almost perfectly correlated with the performance. The correlation is shown in Figure 40. This result gives additional evidence that the “robust” solution will typically equal the “optimal” solution for the specification process.

Correlation betweenCGV casualties and the corresponding variance

Correlations

	Mean(Sqd7Cas)	Variance(Sqd7Cas)
Mean(Sqd7Cas)	1.0000	0.9965
Variance(Sqd7Cas)	0.9965	1.0000

Scatterplot Matrix

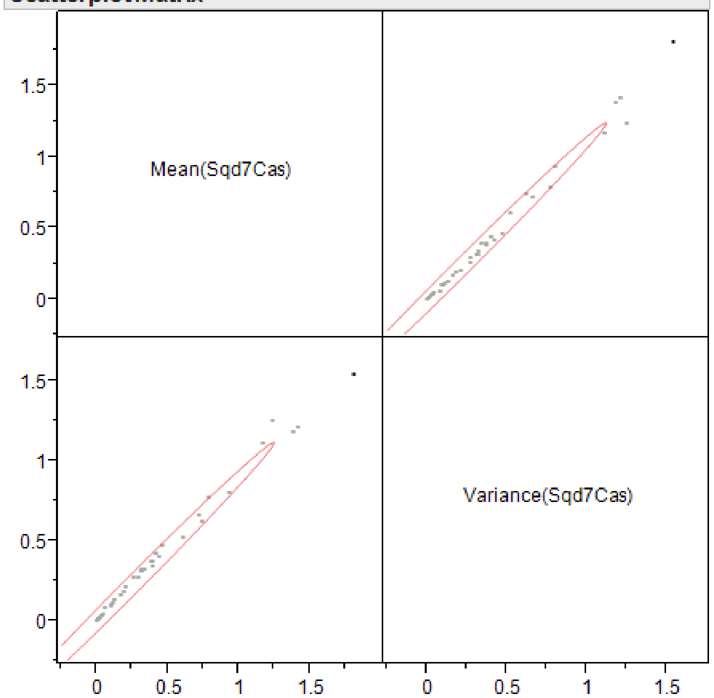


Figure 40. Correlation scatterplot: The x-axis shows the variance and the y-axis the mean CGV casualties. The variance decreases as fast as the mean casualties.

VII. CONCLUSIONS

All findings are based on the underlying scenario and the agent-based software MANA that was used. So, there is no proof that all conclusions are confirmed in reality, but the author is confident that the stated findings can be generalized and will match up with results from real field testing.

A. SIGNIFICANT FINDINGS

The first and most important conclusion is that the chosen approach is feasible for land based systems. The robustness of the regression results and the constancy of the insights for different methods and models, as well as different GCV types, have shown that the method is repeatable under different circumstances and will lead to the same conclusions. Furthermore, the most influential factors for each MOE could be identified and explained. The approach cannot guarantee an optimal solution, but it can give additional insights and direct research and specifications development. A proof can only be conducted if the results are tested under real combat conditions, which is far out of the scope of this thesis.

One of the leading research questions addressed by this thesis was whether the interactions between factors matters. So far, these interactions are not considered in any specification process currently used. The study finds that even when no specific interaction is the most influential factor for a MOE, results were dependent on interactions. Nearly all of the influential interactions are two-way interactions, but also some three-way interactions were found.

Another question this thesis answered was which factors contribute most to the survivability of the GCV under the given conditions. The study shows not only the most influential parameters, but also finds evidence that there is a strong interaction between them and they must be related to one another (Appendix F).

Additionally, the study finds evidence that the most influential factors for overall performance of a ground combat system are heavily dependent on the scenario used. So, there could be some basic requirements for a given scenario which can be shared by all deployed assets and systems to increase the performance of the whole force.

Another argument for using the suggested specification approach is that the study found non-linear relationships between MOEs and factors. These non-linearities are especially hard to foresee if the specification process is based on subject matter expert inputs or battlefield experiences. For example the quadratic relationship for concealment with the MOE “RED casualties” would probably not being addressed by judgment and experience alone.

Finally, the author concludes that the specification process can be improved by implementing the suggested approach in the current process as an additional element.

B. INSIGHT INTO PREDICTED OUTCOMES

Besides finding the answers to the research questions, the author as a student of military history discovered an additional major insight while conducting the analysis. Even with the knowledge of all important battlefield factors like terrain, weather, training levels, equipment deployed, tactics and so on, it is not possible to predict the outcome of a battle. The author can control all these “hard” factors, but the regression models still have minimal explanatory power. The reason is that the variance introduced by the random behavior of the agents (humans)—even when it is controlled by fixed rules (orders)—has much greater influence than bare numbers. So, the models cannot predict the outcome of a single battle, but they can give insight into the odds of winning.

Historians look at one data point (battle) and infer from there the reasons for success or failure, which they see in a summary of factors including leadership and motivation. While there is no doubt that this analysis is useful and can give insights, the author claims that even with all the factors known, the historians are not able to predict a battle’s outcome. In fact, it is much more likely that inferior forces have won battles in history just by randomness and luck than is commonly considered.

C. RECOMMENDATIONS

The author recommends that the outlined approach be used in the preliminary analysis to define specifications and also in cases where specifications must be altered. Specifically, the outlined approach should be used in conjunction with the already existing process rather than as a substitute. The field testing, subject matter expert input, combat simulation tests, and battlefield experience currently used provide essential insights. The more information there is available before the specifications are translated into prototype development, the more savings in time and money can be achieved, and the better the final performance of the GCV will be. Therefore, the approach should be implemented as part of the Department of Defense specification process.

Regardless of which tools are used for finding the specifications of a ground system, it is recommended that at least two-way interactions and non-linear effects be considered as this study showed that they matter.

D. FUTURE RESEARCH

The author acknowledges that this study is not exhaustive and that several aspects of this work can serve as the basis for future research. As a starting point, future research could verify the findings by using different scenarios with the same analysis methods. It would be beneficial to see if the basic conclusions hold in these scenarios and to confirm that major requirements are dependent on the scenario.

Specifically, the author recommends the following approaches for future research:

- Examine different peacekeeping scenarios and focus on different weapon systems to see if their performance depends on similar factors. The final result could be a list of basic requirements for different kind of scenarios to influence future force structures.

- Determine whether the conclusions of this study can be confirmed for the same scenario using a physics-based, high-resolution application such as Combat XXI. (MANA, which was used for our study, is a low resolution model.)
- Use an advanced tool to visualize the tradeoffs between different factors and MOEs. Such a tool will soon be available. One of the outputs of this thesis is to provide a meta-model for the “dashboard” to be implemented by the Systems Engineering Department at NPS. Results will help direct the discussion of the specification process and improve the overall performance of future ground combat systems.

Note: the developed scenario has been used in the capstone project for the SE311 Vehicle Survivability course at the NPS engineering department. (Vehicle Survivability Team & Cohort 311-114G, 2013).

APPENDIX A. VEHICLE SURVIVABILITY FACTOR LIST

The following vehicle survivability factor list (Vehicle Survivability Team & Cohort 311-114G, 2013) is provided to enable a fast comparison of the factors that are considered in this thesis and those which are omitted. The list provides a base for future research and the exploration of additional factors using the described approach.

- **Manage System States**
  - Transition between States
  - Enable / Disable Functions by State
- **Survivability**
  - Avoid Detection
    - Manage Signatures
  - Avoid Acquisition
  - Avoid Hit / Activation of Threat
  - Avoid Penetration
  - Avoid Kill / Incapacitation
    - Protect Personnel
      - Protect Against Acceleration Effects
      - Protect Against Fragments
      - Protect Against Blast Effects
    - Protect Against CBRN
    - Protect Against Fires
    - Protect Against Electromagnetic Effects
- **Mobility**
  - *Traverse Terrain*
    - Traverse Distances
    - Ascend Grades
    - Descend Grades
    - Traverse Lateral Slopes
    - Negotiate Ramps
  - *Control Motion*
    - Control Speed
      - Maintain Speed
      - Increase Speed
      - reduce Speed
      - Hold Vehicle Stationary
  - *Overcome Obstacles*
    - Vertical Step

- Cross Gaps
- Breach Barrier

Transport Loads / Personnel

- *Accommodate Personnel*
    - Carry Personnel
        - Personnel Capacity
    - Secure Personnel
- *Transport Loads*

Situational Awareness

- *Enable Common Situational Understanding*
- *Enable Vision*
    - 360° Situational Awareness
- *Detect Objects*
- *Identify Objects*

Lethality

- *Prioritize Threats*
- *Select Threats*
- *Acquire Threat*
- *Track Threat*
- *Engage Threat*
    - Guide Ammunition to Target
    - Deliver Ammunition to Weapons
        - Track Ammunition Status
    - Control Weapons
- *Host Weapons*
    - Manage Weapon Recoil/Impact
    - Manage Weapon Biproducts

Power Vehicle

- *Generate Electrical Power*
- *Generate Mechanical Power*
- *Distribute Electrical Power*

Mission Command

- *Communications*
    - Communicate Internally
    - Communicate Externally
- *Data Management*

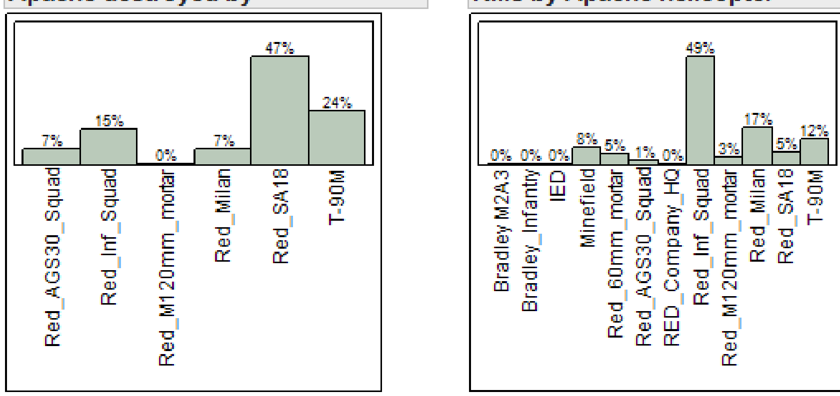
Life Cycle

- *Transportability*
- *Sustainability*
    - Reliability
    - Availability
    - Maintainability

APPENDIX B. DETAILS OF BASIC SCENARIO RUN, 1000 REPLICATIONS

The histograms in this appendix provide additional information about the scenario behavior for the military experienced reader and are important to show the validity of the results. For every agent class the number and type of kills is listed, and in parallel it is shown by which system the agent is killed.

Apache destroyed by | **Kills by Apache helicopter**



Frequencies (Apache destroyed by)

Level	Count	Prob
Red_AGS30_Squad	83	0.06635
Red_Inf_Squad	192	0.15348
Red_M120mm_mortar	1	0.00080
Red_Milan	85	0.06795
Red_SA18	594	0.47482
T-90M	296	0.23661
Total	1251	1.00000

N Missing 0
6 Levels

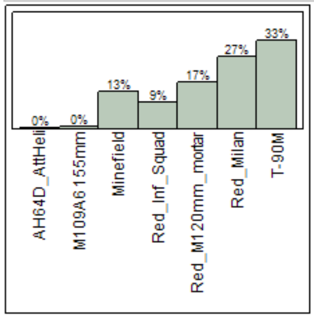
Frequencies (Kills by Apache helicopter)

Level	Count	Prob
Bradley M2A3	1	0.00006
Bradley_Infantry	7	0.00043
IED	21	0.00129
Minefield	1255	0.07680
Red_60mm_mortar	761	0.04657
Red_AGS30_Squad	244	0.01493
RED_Company_HQ	3	0.00018
Red_Inf_Squad	8087	0.49489
Red_M120mm_mortar	534	0.03268
Red_Milan	2702	0.16535
Red_SA18	836	0.05116
T-90M	1890	0.11566
Total	16341	1.00000

N Missing 0
12 Levels

Figure 41. Histogram of Apache helicopter kills and casualties.

Bradley destroyed by

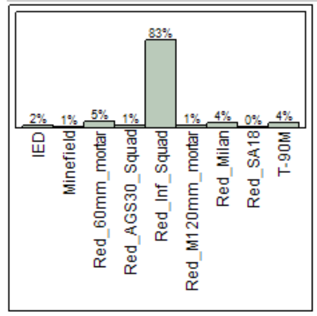


Frequencies

Level	Count	Prob
AH64D_AttHeli	1	0.00050
M109A6 155mm	8	0.00402
Minefield	267	0.13410
Red_Inf_Squad	189	0.09493
Red_M120mm_mortar	340	0.17077
Red_Milan	535	0.26871
T-90M	651	0.32697
Total	1991	1.00000

N Missing 0
7 Levels

Kills by Bradleys



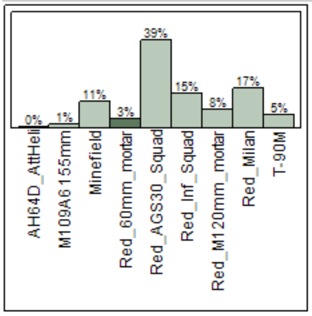
Frequencies

Level	Count	Prob
IED	174	0.01805
Minefield	55	0.00570
Red_60mm_mortar	520	0.05393
Red_AGS30_Squad	91	0.00944
Red_Inf_Squad	7977	0.82732
Red_M120mm_mortar	77	0.00799
Red_Milan	354	0.03671
Red_SA18	28	0.00290
T-90M	366	0.03796
Total	9642	1.00000

N Missing 0
9 Levels

Figure 42. Histogram of Bradley infantry carrier kills and casualties.

BLUE infantry killed by

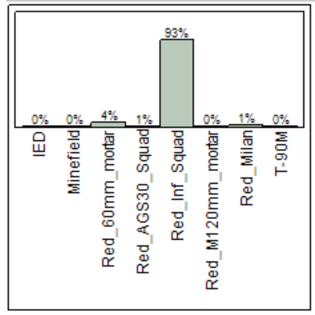


Frequencies

Level	Count	Prob
AH64D_AttHeli	7	0.00044
M109A6 155mm	150	0.00950
Minefield	1763	0.11167
Red_60mm_mortar	527	0.03338
Red_AGS30_Squad	6172	0.39095
Red_Inf_Squad	2345	0.14854
Red_M120mm_mortar	1262	0.07994
Red_Milan	2711	0.17172
T-90M	850	0.05384
Total	15787	1.00000

N Missing 0
9 Levels

Kills by BLUE infantry



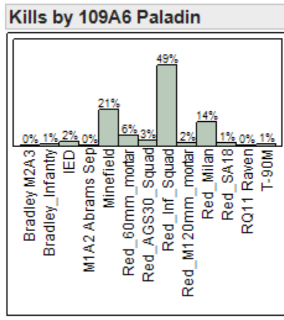
Frequencies

Level	Count	Prob
IED	30	0.00301
Minefield	26	0.00261
Red_60mm_mortar	447	0.04490
Red_AGS30_Squad	56	0.00562
Red_Inf_Squad	9284	0.93250
Red_M120mm_mortar	1	0.00010
Red_Milan	78	0.00783
T-90M	34	0.00342
Total	9956	1.00000

N Missing 0
8 Levels

Figure 43. Histogram of BLUE infantry kills and casualties.

Kills by 109A6 Paladin

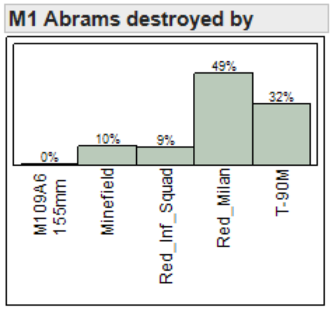


Frequencies

Level	Count	Prob
Bradley M2A3	8	0.00050
Bradley_Infantry	150	0.00942
IED	356	0.02236
M1A2 Abrams Sep	2	0.00013
Minefield	3397	0.21335
Red_60mm_mortar	967	0.06073
Red_AGS30_Squad	511	0.03209
Red_Inf_Squad	7736	0.48587
Red_M120mm_mortar	297	0.01865
Red_Milan	2213	0.13899
Red_SA18	179	0.01124
RQ11 Raven	1	0.00006
T-90M	105	0.00659
Total	15922	1.00000

N Missing 0
13 Levels

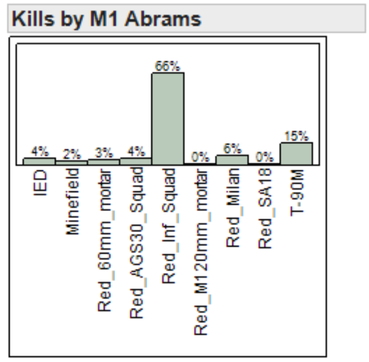
Figure 44. Histogram of 109A6 Paladin kills. The artillery is not in reach of enemy forces, so no casualties occur.



Frequencies

Level	Count	Prob
M109A6 155mm	2	0.00121
Minefield	162	0.09783
Red_Inf_Squad	145	0.08756
Red_Milan	813	0.49094
T-90M	534	0.32246
Total	1656	1.00000

N Missing 0
5 Levels

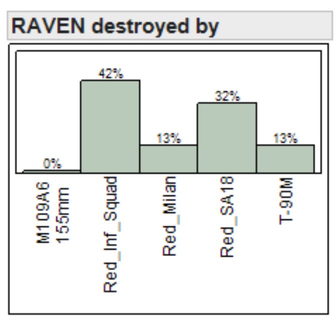


Frequencies

Level	Count	Prob
IED	419	0.03986
Minefield	234	0.02226
Red_60mm_mortar	305	0.02901
Red_AGS30_Squad	375	0.03567
Red_Inf_Squad	6951	0.66118
Red_M120mm_mortar	12	0.00114
Red_Milan	607	0.05774
Red_SA18	5	0.00048
T-90M	1605	0.15267
Total	10513	1.00000

N Missing 0
9 Levels

Figure 45. Histogram of M1 Abrams kills and casualties.



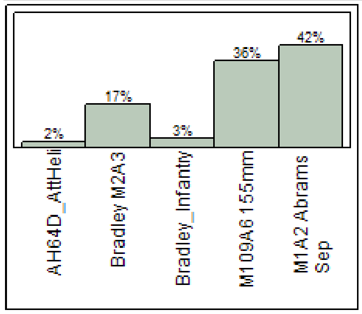
Frequencies

Level	Count	Prob
M109A6 155mm	1	0.00488
Red_Inf_Squad	87	0.42439
Red_Milan	26	0.12683
Red_SA18	65	0.31707
T-90M	26	0.12683
Total	205	1.00000

N Missing 0
5 Levels

Figure 46. Histogram of RAVEN UAV casualties. As the RAVEN has no weapon systems, no kills of enemy weapon systems occur.

IED detected through



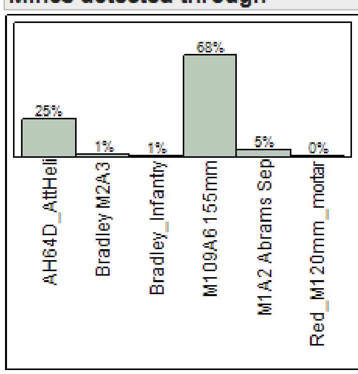
Frequencies

Level	Count	Prob
AH64D_AttHeli	21	0.02100
Bradley M2A3	174	0.17400
Bradley_Infantry	30	0.03000
M109A6 155mm	356	0.35600
M1A2 Abrams Sep	419	0.41900
Total	1000	1.00000

N Missing 0
5 Levels

Figure 47. Histogram of IED detection. Notice that detection through artillery represents detection through any other asset as artillery has no sensors of its own. It is stated in the histogram as artillery since it is used to destroy the IEDs which represents the detection and clearance in the simualtion.

Mines detected through

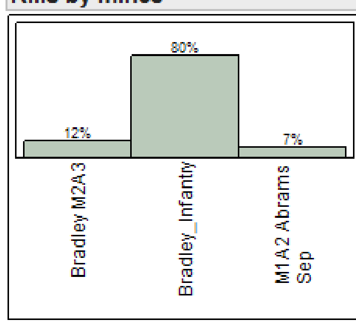


Frequencies

Level	Count	Prob
AH64D_AttHeli	1255	0.25246
Bradley M2A3	55	0.01106
Bradley_Infantry	26	0.00523
M109A6 155mm	3397	0.68336
M1A2 Abrams Sep	234	0.04707
Red_M120mm_mortar	4	0.00080
Total	4971	1.00000

N Missing 0
6 Levels

Kills by mines



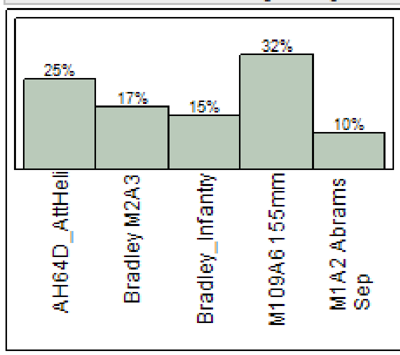
Frequencies

Level	Count	Prob
Bradley M2A3	267	0.12181
Bradley_Infantry	1763	0.80429
M1A2 Abrams Sep	162	0.07391
Total	2192	1.00000

N Missing 0
3 Levels

Figure 48. Histogram of mines detection and kills.

60 mm mortar destroyed by

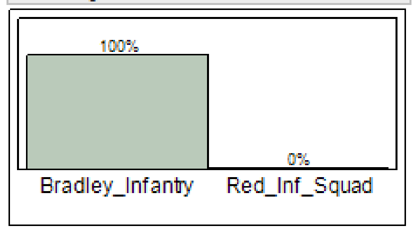


Frequencies

Level	Count	Prob
AH64D_AttHeli	761	0.25367
Bradley M2A3	520	0.17333
Bradley_Infantry	447	0.14900
M109A6 155mm	967	0.32233
M1A2 Abrams Sep	305	0.10167
Total	3000	1.00000

N Missing 0
5 Levels

Kills by 60 mm mortar



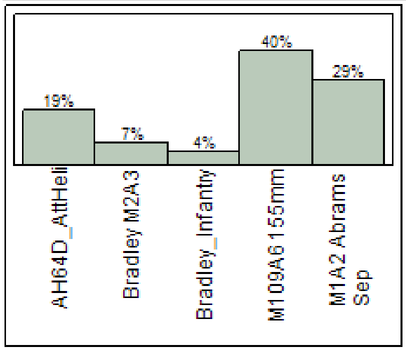
Frequencies

Level	Count	Prob
Bradley_Infantry	527	0.99811
Red_Inf_Squad	1	0.00189
Total	528	1.00000

N Missing 0
2 Levels

Figure 49. Histogram of RED 60 mm mortar casualties and kills.

AGS30 destroyed by

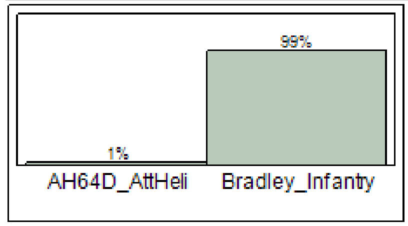


Frequencies

Level	Count	Prob
AH64D_AttHeli	244	0.19107
Bradley M2A3	91	0.07126
Bradley_Infantry	56	0.04385
M109A6 155mm	511	0.40016
M1A2 Abrams Sep	375	0.29366
Total	1277	1.00000

N Missing 0
5 Levels

Kills by AGS 30



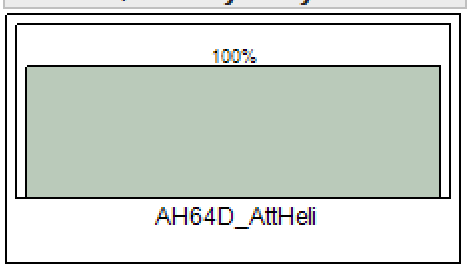
Frequencies

Level	Count	Prob
AH64D_AttHeli	83	0.01327
Bradley_Infantry	6172	0.98673
Total	6255	1.00000

N Missing 0
2 Levels

Figure 50. Histogram of RED AGS30 casualties and kills.

RED HQ destroyed by



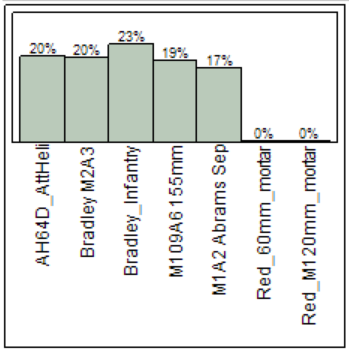
Frequencies

Level	Count	Prob
AH64D_AttHeli	3	1.00000
Total	3	1.00000

N Missing 0
1 Levels

Figure 51. Histogram of RED HQ casualties.

RED infantry killed by

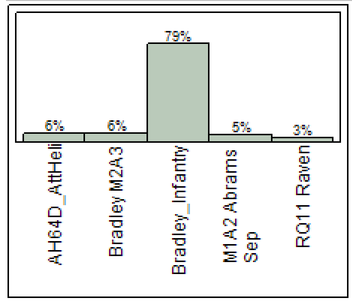


Frequencies

Level	Count	Prob
AH64D_AttHeli	8087	0.20198
Bradley M2A3	7977	0.19923
Bradley_Infantry	9284	0.23187
M109A6 155mm	7736	0.19321
M1A2 Abrams Sep	6951	0.17361
Red_60mm_mortar	1	0.00002
Red_M120mm_mortar	3	0.00007
Total	40039	1.00000

N Missing 0
7 Levels

Kills by RED infantry



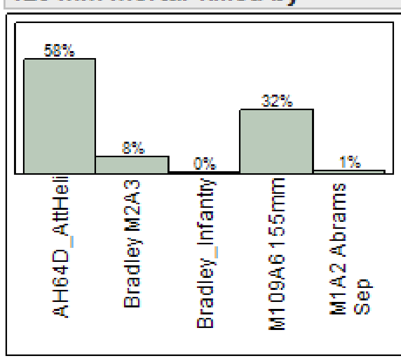
Frequencies

Level	Count	Prob
AH64D_AttHeli	192	0.06491
Bradley M2A3	189	0.06389
Bradley_Infantry	2345	0.79277
M1A2 Abrams Sep	145	0.04902
RQ11 Raven	87	0.02941
Total	2958	1.00000

N Missing 0
5 Levels

Figure 52. Histogram of RED infantry casualties and kills.

120 mm mortar killed by

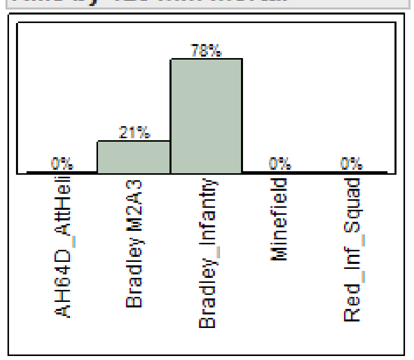


Frequencies

Level	Count	Prob
AH64D_AttHeli	534	0.57980
Bradley M2A3	77	0.08360
Bradley_Infantry	1	0.00109
M109A6 155mm	297	0.32248
M1A2 Abrams Sep	12	0.01303
Total	921	1.00000

N Missing 0
5 Levels

Kills by 120 mm mortar



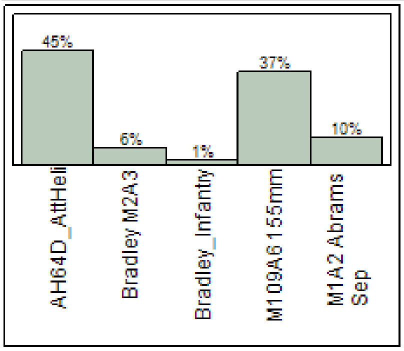
Frequencies

Level	Count	Prob
AH64D_AttHeli	1	0.00062
Bradley M2A3	340	0.21118
Bradley_Infantry	1262	0.78385
Minefield	4	0.00248
Red_Inf_Squad	3	0.00186
Total	1610	1.00000

N Missing 0
5 Levels

Figure 53. Histogram of RED 120 mm mortar casualties and kills.

MILAN destroyed by

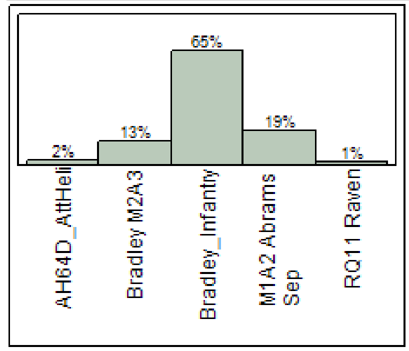


Frequencies

Level	Count	Prob
AH64D_AttHeli	2702	0.45381
Bradley M2A3	354	0.05946
Bradley_Infantry	78	0.01310
M109A6 155mm	2213	0.37168
M1A2 Abrams Sep	607	0.10195
Total	5954	1.00000

N Missing 0
5 Levels

Kills by MILAN



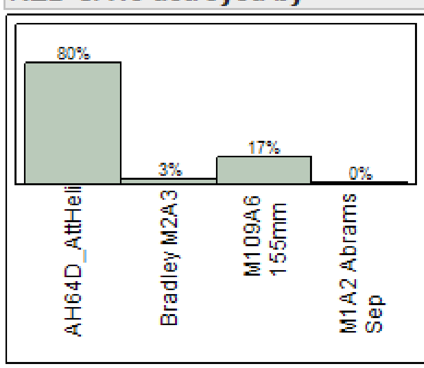
Frequencies

Level	Count	Prob
AH64D_AttHeli	85	0.02038
Bradley M2A3	535	0.12830
Bradley_Infantry	2711	0.65012
M1A2 Abrams Sep	813	0.19496
RQ11 Raven	26	0.00624
Total	4170	1.00000

N Missing 0
5 Levels

Figure 54. Histogram of RED MILAN casualties and kills.

RED SA18 detroyed by

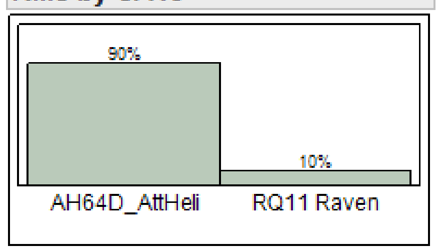


Frequencies

Level	Count	Prob
AH64D_AttHeli	836	0.79771
Bradley M2A3	28	0.02672
M109A6 155mm	179	0.17080
M1A2 Abrams Sep	5	0.00477
Total	1048	1.00000

N Missing 0
4 Levels

Kills by SA18



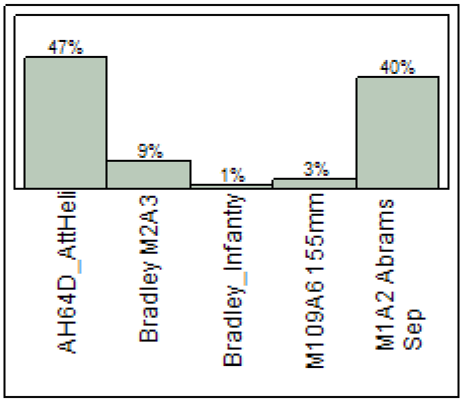
Frequencies

Level	Count	Prob
AH64D_AttHeli	594	0.90137
RQ11 Raven	65	0.09863
Total	659	1.00000

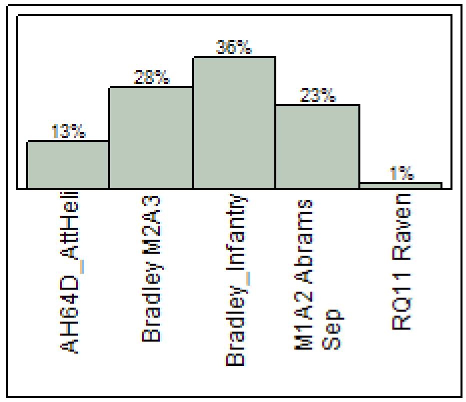
N Missing 0
2 Levels

Figure 55. Histogram of RED SA 18 casualties and kills.

T90M destroyed by



Kills by T90M



Frequencies

Level	Count	Prob
AH64D_AttHeli	1890	0.47250
Bradley M2A3	366	0.09150
Bradley_Infantry	34	0.00850
M109A6 155mm	105	0.02625
M1A2 Abrams Sep	1605	0.40125
Total	4000	1.00000

N Missing 0
5 Levels

Frequencies

Level	Count	Prob
AH64D_AttHeli	296	0.12558
Bradley M2A3	651	0.27620
Bradley_Infantry	850	0.36063
M1A2 Abrams Sep	534	0.22656
RQ11 Raven	26	0.01103
Total	2357	1.00000

N Missing 0
5 Levels

Figure 56. Histogram of RED T90M casualties and kills.

APPENDIX C. DOE FOR INFANTRY CARRIER GCV

The DOE spreadsheet used for the infantry carrier GCV is shown below. The spreadsheet shows how the values of the factors are implemented for the supper cluster runs and shall enable future researcher to do the same.

low level	1	1	40	300	7	0.8	0.8	0.8	0.8	0.8	0	0.1	0.1	0.1
high level	3	99	60	1000	10	2	2	2	2	2	1	1	1	1
decimals	0	0	0	0	0	4	4	4	4	4	0	4	4	4
factor name	#hits	conceal	speed	armor	inf	DetInf	DetVeh	Bushm	NG	TOW	Mortar	CentricW	EW	actDef
	2	6	47	530	7	1.7188	1.7563	1.3813	1.9625	1.6625	1	0.9438	0.2688	0.6625
	3	71	42	595	8	1.1	1.4563	1.7	1.6625	1.9063	1	0.5359	0.3109	0.4094
	3	36	59	453	8	1.8313	0.9875	1.3438	1.2875	1.4938	1	0.8875	0.5219	0.5641
	2	88	54	617	7	1.3063	1.1188	1.1188	0.95	1.9813	1	0.6625	0.1703	0.2828
	3	47	44	311	7	0.9875	1.1	1.5313	1.5313	1.3813	0	0.8594	0.6766	0.6344
	2	91	45	639	7	1.5875	0.9688	1.8313	1.8688	0.9313	0	0.8031	0.9016	0.1563
	3	19	51	322	8	1.1938	1.8688	1.3063	0.9875	1.325	0	0.9156	0.9578	0.7609
	3	76	58	519	8	1.9063	1.6438	0.8188	1.1	1.175	0	0.6766	0.7469	0.1281
	2	4	40	869	8	1.5313	1.2688	0.9125	1.7563	1.1563	1	0.4516	0.3953	0.3109
	3	68	50	836	7	1.1375	1.9063	1.25	1.6063	0.8	1	0.1281	0.4797	0.8594
	2	3	59	672	8	1.325	1.175	1.625	0.8188	1.0813	1	0.2688	0.2969	0.1422
	3	52	54	945	8	0.875	1.25	1.775	1.175	1.25	1	0.325	0.5078	0.6203
	2	22	47	748	8	1.3813	1.025	1.1375	1.9438	1.9438	0	0.1422	0.9859	0.2547
	3	55	48	923	8	1.9625	0.8563	0.8	1.4188	1.4375	0	0.3672	0.5641	0.7047
	2	33	56	967	8	1.0625	1.3625	1.925	0.9688	1.7938	0	0.4938	0.9719	0.3672
	2	58	51	803	7	1.9438	2	1.475	1.3438	1.775	0	0.1984	0.7188	0.9859
	3	44	48	388	9	2	1.7375	1.9625	1.4938	1.5125	0	0.3531	0.4656	0.6766
	2	85	45	541	9	1.3438	1.7938	1.7563	1.2313	1.6813	0	0.1	0.1	0.1703
	2	39	51	508	9	1.8688	0.8375	1.2875	1.4375	1.7563	0	0.1703	0.2828	0.8875
	2	73	57	344	9	1.0063	1.325	1.0063	1.775	1.85	0	0.4797	0.2547	0.325
	3	21	48	366	10	1.25	0.8188	1.6438	1.1563	0.9125	0	0.2547	0.6484	0.8313
	3	82	40	409	9	1.6438	1.3813	1.8688	1.0063	1.2125	1	0.3813	0.7609	0.2266
	3	41	56	475	10	0.95	1.6625	0.95	1.475	1.1938	1	0.3391	0.6063	0.5922
	2	99	57	563	9	1.4375	1.4938	1.0625	2	0.875	1	0.2828	0.8734	0.2969
	2	26	42	716	9	1.6813	1.925	0.9875	0.9125	0.9875	0	0.6906	0.2125	0.1
	3	62	43	1000	9	1.025	1.5688	1.2313	1.25	1.3438	0	0.8734	0.4094	0.6063
	3	10	55	858	9	1.8875	1.1938	1.9438	1.7188	1.1	0	0.6344	0.3672	0.1984
	3	84	53	880	10	1.175	0.95	1.5875	1.6813	1.2313	0	0.9859	0.1563	0.7469
	3	30	43	727	9	1.0438	1.2875	0.8938	1.0625	1.8313	1	0.5922	0.9156	0.3813
	2	93	47	814	10	1.9813	1.2125	1.4375	0.875	1.7375	1	0.7047	0.8594	0.6484
	2	13	54	694	10	1.2875	1.7188	1.7188	1.9063	1.9625	1	0.5781	0.775	0.1844
	3	65	59	902	9	1.5688	1.8875	1.6063	1.5875	1.5313	1	0.7891	0.6625	0.5781
	2	50	50	650	9	1.4	1.4	1.4	1.4	1.4	1	0.55	0.55	0.55
	2	94	53	770	10	1.0813	1.0438	1.4188	0.8375	1.1375	0	0.1563	0.8313	0.4375
	1	29	58	705	9	1.7	1.3438	1.1	1.1375	0.8938	0	0.5641	0.7891	0.6906
	1	64	41	847	9	0.9688	1.8125	1.4563	1.5125	1.3063	0	0.2125	0.5781	0.5359
	2	12	46	683	10	1.4938	1.6813	1.6813	1.85	0.8188	0	0.4375	0.9297	0.8172
	1	53	56	989	10	1.8125	1.7	1.2688	1.2688	1.4188	1	0.2406	0.4234	0.4656
	2	9	55	661	10	1.2125	1.8313	0.9688	0.9313	1.8688	1	0.2969	0.1984	0.9438
	1	81	49	978	9	1.6063	0.9313	1.4938	1.8125	1.475	1	0.1844	0.1422	0.3391
	1	24	42	781	9	0.8938	1.1563	1.9813	1.7	1.625	1	0.4234	0.3531	0.9719
	2	96	60	431	9	1.2688	1.5313	1.8875	1.0438	1.6438	0	0.6484	0.7047	0.7891
	1	32	50	464	10	1.6625	0.8938	1.55	1.1938	2	0	0.9719	0.6203	0.2406
	2	97	41	628	9	1.475	1.625	1.175	1.9813	1.7188	0	0.8313	0.8031	0.9578
	1	48	46	355	9	1.925	1.55	1.025	1.625	1.55	0	0.775	0.5922	0.4797
	2	78	53	552	9	1.4188	1.775	1.6625	0.8563	0.8563	1	0.9578	0.1141	0.8453
	1	45	52	377	9	0.8375	1.9438	2	1.3813	1.3625	1	0.7328	0.5359	0.3953
	2	67	44	333	9	1.7375	1.4375	0.875	1.8313	1.0063	1	0.6063	0.1281	0.7328
	2	42	49	497	10	0.8563	0.8	1.325	1.4563	1.025	1	0.9016	0.3813	0.1141
	1	56	52	913	8	0.8	1.0625	0.8375	1.3063	1.2875	1	0.7469	0.6344	0.4234
	2	15	55	759	8	1.4563	1.0063	1.0438	1.5688	1.1188	1	1	1	0.9297
	2	61	49	792	8	0.9313	1.9625	1.5125	1.3625	1.0438	1	0.9297	0.8172	0.2125
	2	27	43	956	8	1.7938	1.475	1.7938	1.025	0.95	1	0.6203	0.8453	0.775
	1	79	52	934	7	1.55	1.9813	1.1563	1.6438	1.8875	1	0.8453	0.4516	0.2688
	1	18	60	891	8	1.1563	1.4188	0.9313	1.7938	1.5875	0	0.7188	0.3391	0.8734
	1	59	44	825	7	1.85	1.1375	1.85	1.325	1.6063	0	0.7609	0.4938	0.5078
	2	1	43	738	8	1.3625	1.3063	1.7375	0.8	1.925	0	0.8172	0.2266	0.8031
	2	75	58	584	8	1.1188	0.875	1.8125	1.8875	1.8125	1	0.4094	0.8875	1
	2	38	57	300	8	1.775	1.2313	1.5688	1.55	1.4563	1	0.2266	0.6906	0.4938
	1	90	45	442	8	0.9125	1.6063	0.8563	1.0813	1.7	1	0.4656	0.7328	0.9016
	1	16	48	420	7	1.625	1.85	1.2125	1.1188	1.5688	1	0.1141	0.9438	0.3531
	1	70	58	573	8	1.7563	1.5125	1.9063	1.7375	0.9688	0	0.5078	0.1844	0.7188
	2	7	53	486	7	0.8188	1.5875	1.3625	1.925	1.0625	0	0.3953	0.2406	0.4516
	2	87	46	606	7	1.5125	1.0813	1.0813	0.8938	0.8375	0	0.5219	0.325	0.9156
	1	35	41	398	8	1.2313	0.9125	1.1938	1.2125	1.2688	0	0.3109	0.4375	0.5219

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APPENDIX D. MAIN EFFECT REGRESSION MODELS FOR THE INFANTRY CARRIER GCV

The following regression models are provided to give the reader the underlying analysis results for the stated insights and conclusions in the study. Furthermore, the main effect models may be used as a reference for further research.

Mean (BLUE casualties)

Summary of Fit

RSquare	0.852537
RSquare Adj	0.807395
Root Mean Square Error	1.636819
Mean of Response	21.28642
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	21.550923	0.213199	101.08	<.0001*
inf	3.2318208	0.320217	10.09	<.0001*
DetVeh	-2.485354	0.349863	-7.10	<.0001*
DetInf	-2.296992	0.351102	-6.54	<.0001*
conceal	-1.626833	0.346849	-4.69	<.0001*
#hits[2]	-1.077852	0.272248	-3.96	0.0002*
Mortar[1]	-0.722422	0.210467	-3.43	0.0012*
Mortar[0]	0.7224218	0.210467	3.43	0.0012*
EW	-1.020703	0.347749	-2.94	0.0051*
#hits[3]	0.7754589	0.319214	2.43	0.0188*
TOW	0.7257297	0.350118	2.07	0.0435*
amor	0.4768492	0.349109	1.37	0.1782
actDef	0.3352609	0.347691	0.96	0.3397
#hits[1]	0.3023935	0.325049	0.93	0.3568
Bushm	0.2519394	0.34857	0.72	0.4733
MG	-0.108403	0.347869	-0.31	0.7567
CentricW	0.0508008	0.3478	0.15	0.8845
speed	0.0047521	0.349221	0.01	0.9892

Mean (RED casualties)

Summary of Fit

RSquare	0.859235
RSquare Adj	0.816144
Root Mean Square Error	0.325639
Mean of Response	64.41632
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	64.353216	0.042415	1517.23	<.0001*
Mortar[0]	-0.544554	0.041872	-13.01	<.0001*
Mortar[1]	0.5445539	0.041872	13.01	<.0001*
#hits[1]	-0.450331	0.064667	-6.96	<.0001*
DetInf	0.4630952	0.06985	6.63	<.0001*
actDef	-0.285944	0.069172	-4.13	0.0001*
#hits[3]	0.243203	0.063506	3.83	0.0004*
#hits[2]	0.2071284	0.054163	3.82	0.0004*
TOW	0.2170326	0.069655	3.12	0.0031*
conceal	-0.209383	0.069004	-3.03	0.0039*
amor	0.1533115	0.069454	2.21	0.0320*
DetVeh	-0.113257	0.069604	-1.63	0.1101
CentricW	0.0521457	0.069194	0.75	0.4547
inf	-0.036863	0.063706	-0.58	0.5655
EW	-0.033741	0.069183	-0.49	0.6279
MG	-0.03292	0.069207	-0.48	0.6364
speed	-0.021665	0.069476	-0.31	0.7565
Bushm	0.0081386	0.069347	0.12	0.9071

Figure 57. Main effect regression models for “BLUE casualties” and “RED casualties.” The regression is done on the means.

Mean (Battle duration)

Summary of Fit

RSquare	0.777885
RSquare Adj	0.709891
Root Mean Square Error	785.9489
Mean of Response	16917.05
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	16917.675	102.3713	165.26	<.0001*
conceal	-1421.536	166.5462	-8.54	<.0001*
DetVeh	-1009.366	167.9931	-6.01	<.0001*
#hits[3]	540.68256	153.2765	3.53	0.0009*
DetInf	-585.8182	168.5883	-3.47	0.0011*
#hits[1]	-524.6483	156.0784	-3.36	0.0015*
Mortar[0]	324.8039	101.0597	3.21	0.0023*
Mortar[1]	-324.8039	101.0597	-3.21	0.0023*
MG	-396.8807	167.0358	-2.38	0.0215*
speed	-382.5328	167.6849	-2.28	0.0269*
armor	305.1714	167.6313	1.82	0.0748
inf	-270.8042	153.758	-1.76	0.0844
EW	-232.496	166.978	-1.39	0.1701
actDef	124.90921	166.9503	0.75	0.4579
TOW	-106.7377	168.1154	-0.63	0.5284
Bushm	-85.44519	167.3722	-0.51	0.6120
#hits[2]	-16.03427	130.725	-0.12	0.9029
CentricW	-6.305879	167.0028	-0.04	0.9700

Mean (casualty ratio)

Summary of Fit

RSquare	0.773883
RSquare Adj	0.704664
Root Mean Square Error	0.841071
Mean of Response	4.643283
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4.4984432	0.109551	41.06	<.0001*
Mortar[0]	-0.79804	0.108148	-7.38	<.0001*
Mortar[1]	0.79804	0.108148	7.38	<.0001*
DetInf	1.1111342	0.180412	6.16	<.0001*
conceal	0.7465357	0.178227	4.19	0.0001*
#hits[2]	0.5469666	0.139893	3.91	0.0003*
inf	-0.525414	0.164542	-3.19	0.0025*
DetVeh	0.4987241	0.179775	2.77	0.0078*
actDef	-0.460139	0.178659	-2.58	0.0131*
#hits[1]	-0.412075	0.167025	-2.47	0.0172*
EW	0.4112472	0.178689	2.30	0.0257*
MG	0.2709632	0.178751	1.52	0.1360
TOW	-0.254516	0.179906	-1.41	0.1635
#hits[3]	-0.134892	0.164026	-0.82	0.4148
Bushm	-0.13222	0.179111	-0.74	0.4639
armor	-0.035521	0.179388	-0.20	0.8439
CentricW	0.0197134	0.178716	0.11	0.9126
speed	0.0194651	0.179445	0.11	0.9141

Figure 58. Main effect regression models for "Battle duration" and "casualty ratio." The regression is done on the means.

Mean (GCV casualties)

Summary of Fit

RSquare	0.818877
RSquare Adj	0.763431
Root Mean Square Error	0.211448
Mean of Response	0.302441
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expandedto all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.3620782	0.027541	13.15	<.0001*
#hits[1]	0.5512428	0.041991	13.13	<.0001*
#hits[3]	-0.334081	0.041237	-8.10	<.0001*
#hits[2]	-0.217161	0.03517	-6.17	<.0001*
actDef	0.1924409	0.044915	4.28	<.0001*
armor	-0.18305	0.045099	-4.06	0.0002*
TOW	-0.139502	0.045229	-3.08	0.0033*
conceal	-0.114508	0.044807	-2.56	0.0138*
Mortar[0]	0.0677214	0.027189	2.49	0.0162*
Mortar[1]	-0.067721	0.027189	-2.49	0.0162*
speed	0.0755876	0.045113	1.68	0.1002
DetInf	-0.042322	0.045356	-0.93	0.3553
DetVeh	-0.019735	0.045196	-0.44	0.6643
CentricW	0.0152254	0.04493	0.34	0.7362
Bushm	0.0142967	0.045029	0.32	0.7522
EW	-0.004277	0.044923	-0.10	0.9245
inf	-0.003694	0.041366	-0.09	0.9292
MG	-0.000894	0.044938	-0.02	0.9842

Figure 59. Main effect regression models for “GCV casualties.” The regression is done on the mean.

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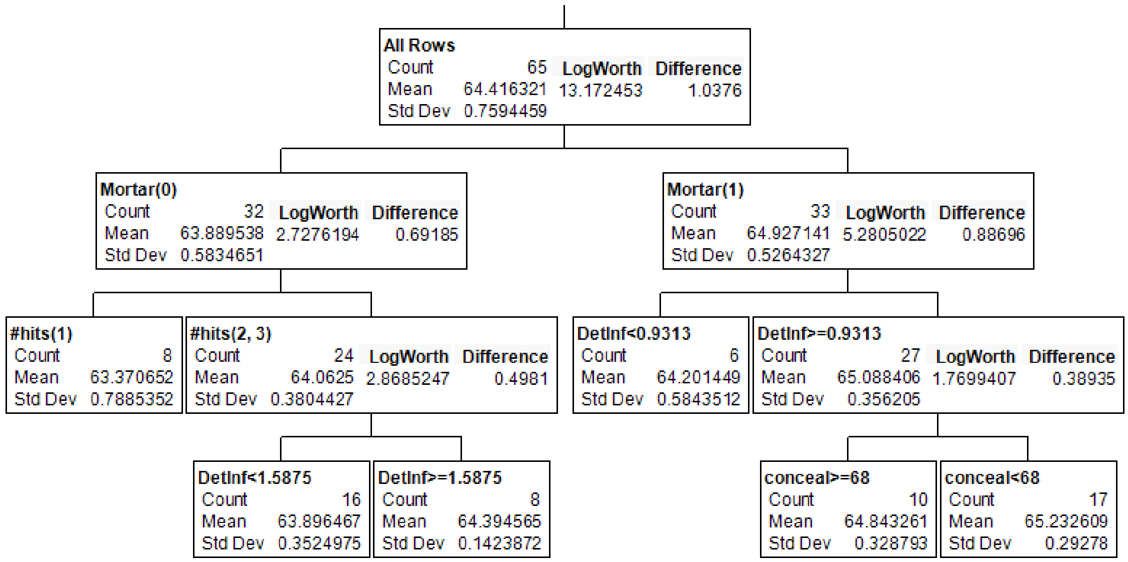
APPENDIX E. PARTITION TREES

The following graphs show the results for the partition tree models. They provide important factor thresholds and a picture of the split analysis process.

"RED casualties"



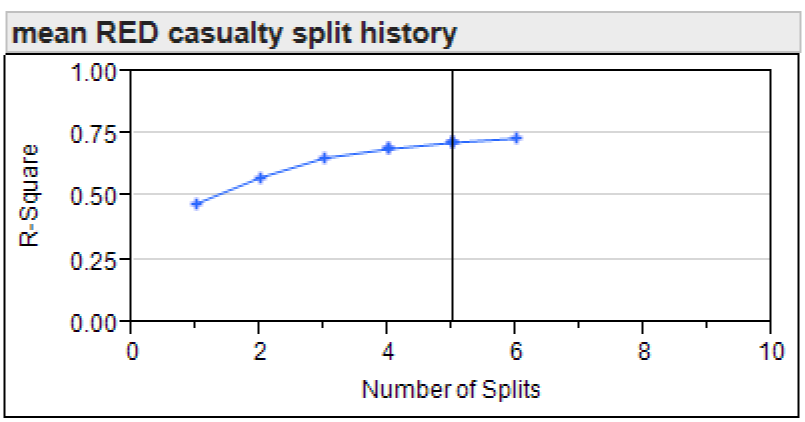
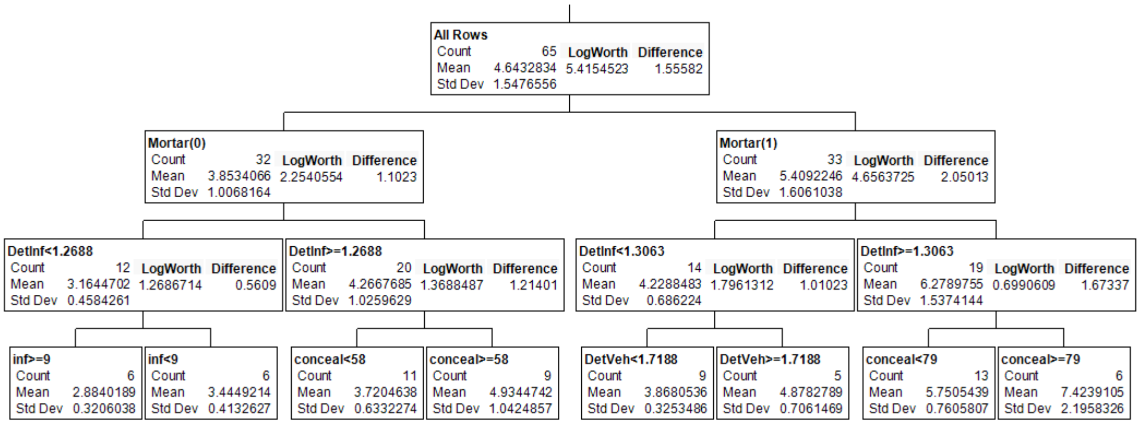


Figure 60. Partition tree and split history for the "RED casualty" MOE. The analysis is conducted on the mean "RED casualty."

“casualty ratio”



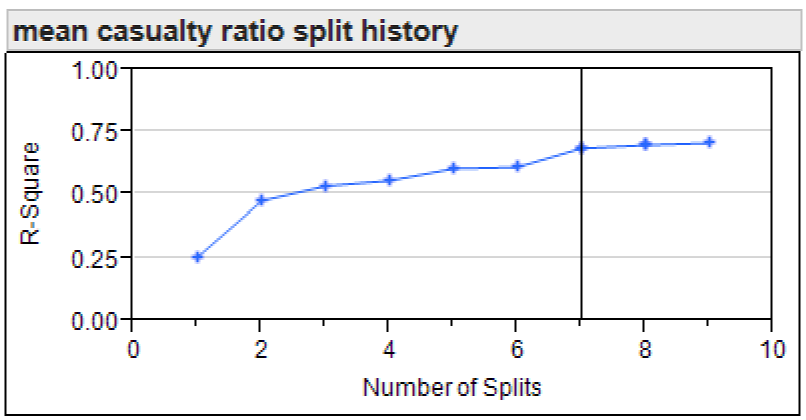


Figure 61. Partition tree and split history for the “casualty ratio” MOE. The analysis is conducted on the mean “casualty ratio.”

“Battle duration”

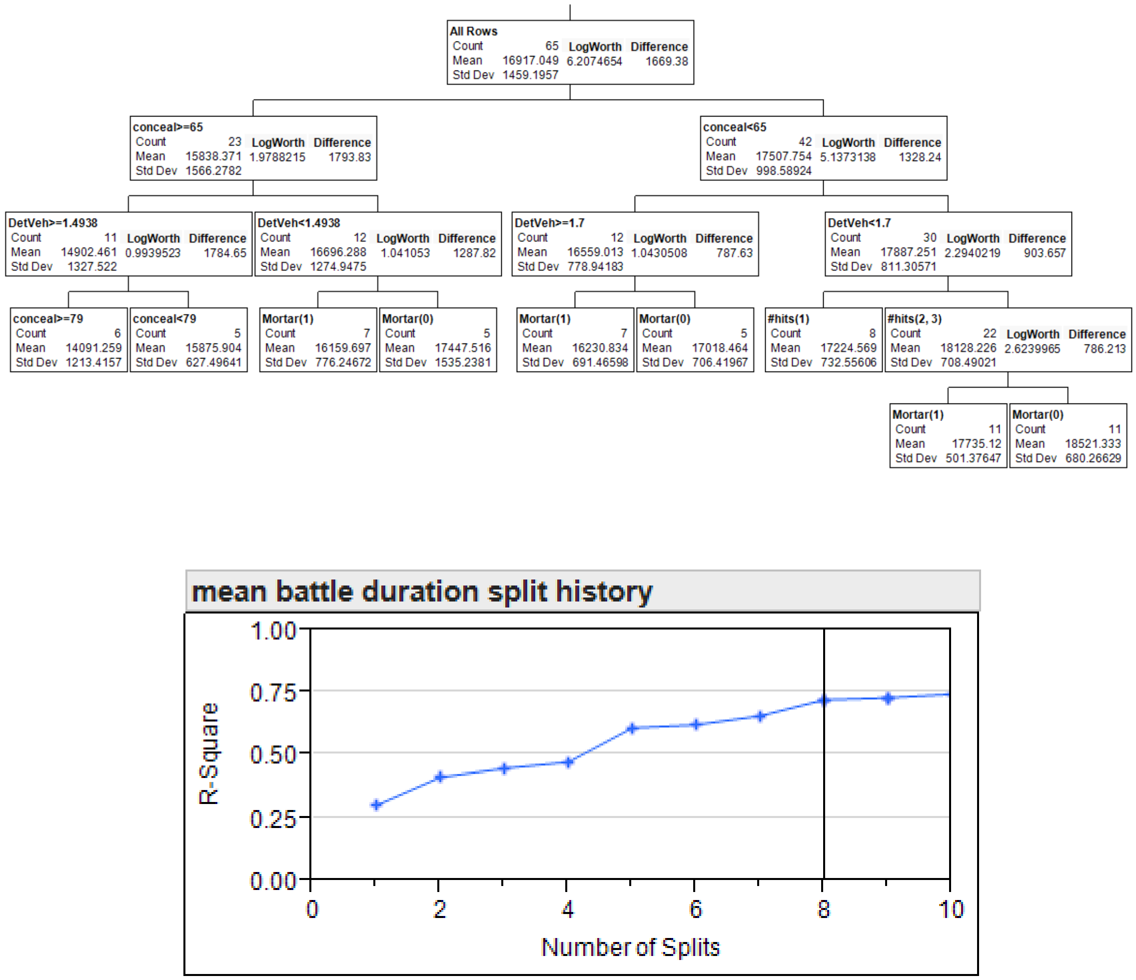
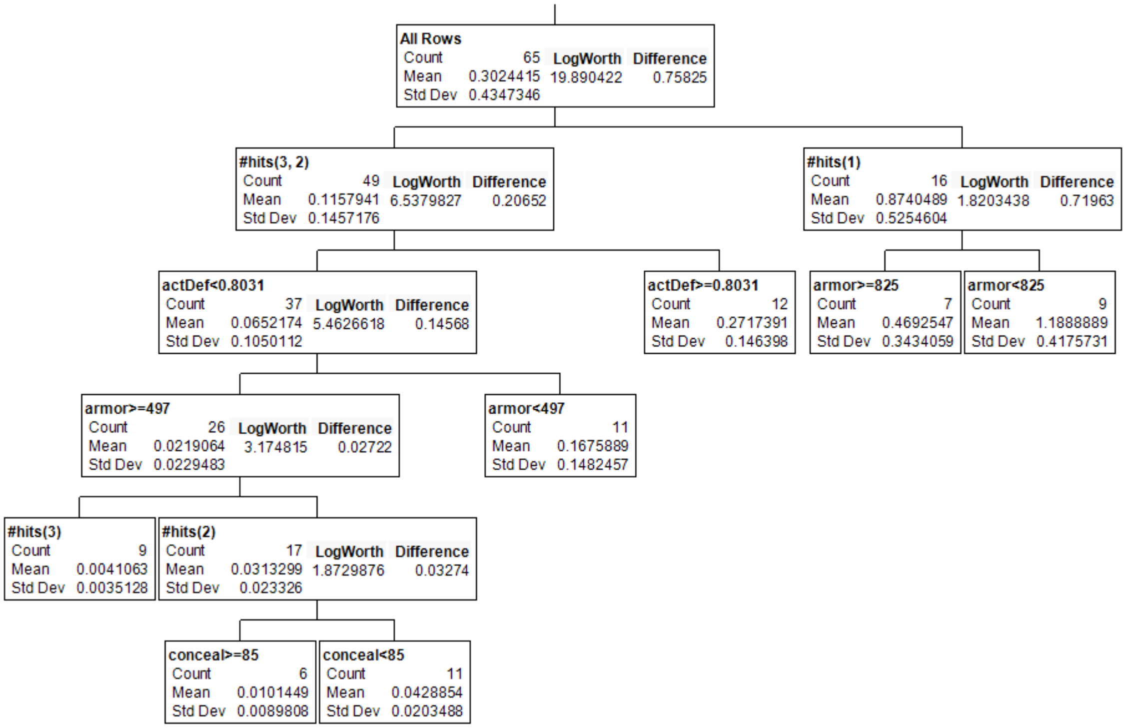


Figure 62. Partition tree and split history for the “Battle duration” MOE. The analysis is conducted on the mean “Battle duration.”

“GCV casualties”



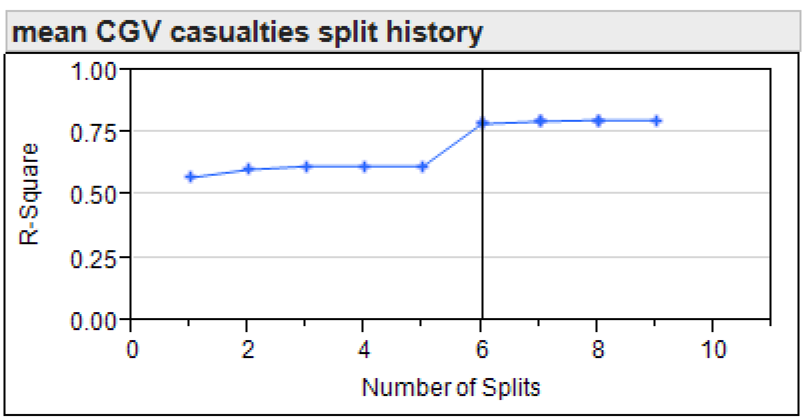


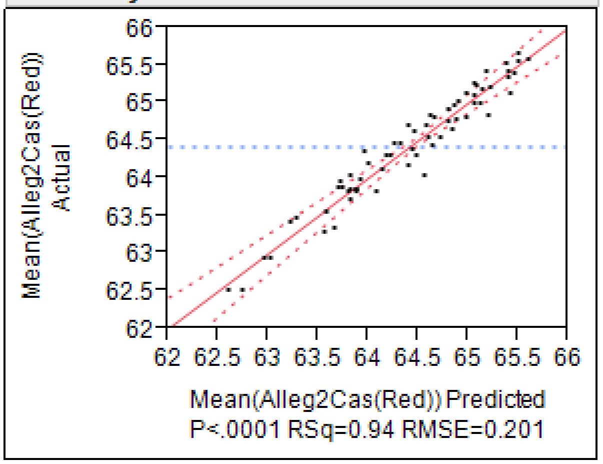
Figure 63. Partition tree and split history for the “GCV casualties” MOE. The analysis is conducted on the mean “GCV casualty.”

APPENDIX F. INFANTRY CARRYING GCV ADVANCED REGRESSION MODELS

The following results show the final regression model with interactions and non-linearities. They will be combined into the “dashboard” in future research and are the final analysis results of the conducted study. Each regression model is presented with its “actual observed vs. prediction” plot to show how close the model is at the observed values. Furthermore, the “summary statistics” for the model are stated, and the model itself is shown with each implemented factor. Finally, the “Prediction profiler” gives a graphical representation of how variable the model is for changes in each included main effect.

“RED casualties”

Actual by Predicted Plot



Summary of Fit

RSquare	0.94416
RSquare Adj	0.929926
Root Mean Square Error	0.201036
Mean of Response	64.41632
Observations (or Sum Wgts)	65

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Mortar[0]	-0.508206	0.025915	-19.61	<.0001*
#hits{1-3&2}	-0.395458	0.031127	-12.70	<.0001*
DetInf	0.6983606	0.073699	9.48	<.0001*
actDef	-0.647575	0.098115	-6.60	<.0001*
(#hits{1-3&2}+0.50769)*(TOW-1.40002)	0.6369239	0.102054	6.24	<.0001*
TOW	0.4493304	0.074526	6.03	<.0001*
conceal	-0.00481	0.000876	-5.49	<.0001*
(conceal-50.0154)*(conceal-50.0154)	-0.000121	0.000036	-3.38	0.0014*
(#hits{1-3&2}+0.50769)*(actDef-0.55001)	-0.453414	0.134778	-3.36	0.0015*
armor	0.000412	0.000124	3.32	0.0016*
(#hits{1-3&2}+0.50769)*(armor-650.031)	0.000381	0.000133	2.87	0.0060*
(conceal-50.0154)*Mortar[0]	0.0024917	0.000886	2.81	0.0070*
DetVeh	-0.171309	0.071683	-2.39	0.0206*

Prediction Profiler

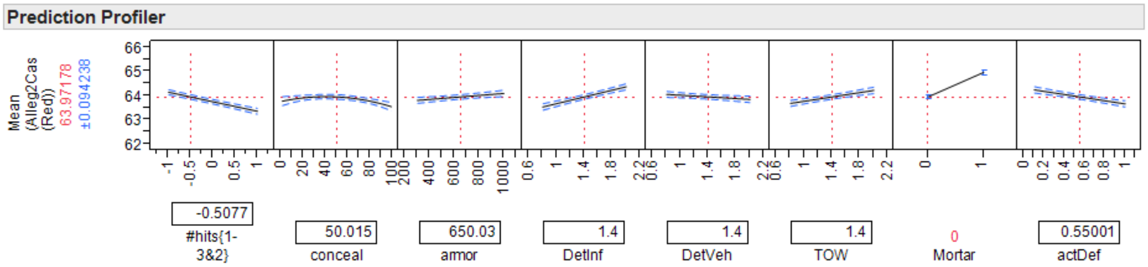
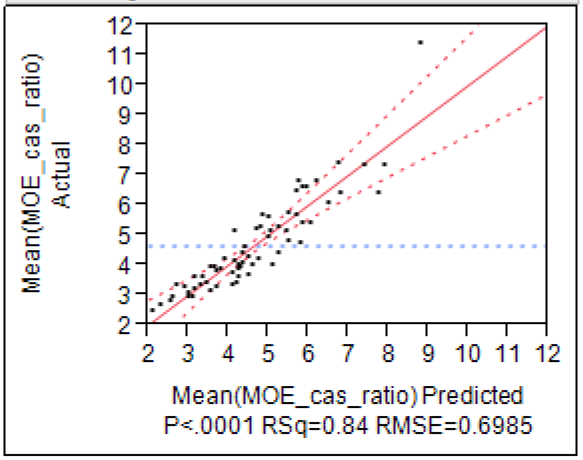


Figure 64. Advanced regression model for “RED casualties” conducted on the MOE mean.

“Casualty ratio”

Actual by Predicted Plot



Summary of Fit

RSquare	0.837682
RSquare Adj	0.796307
Root Mean Square Error	0.698494
Mean of Response	4.643283
Observations (or Sum Wgts)	65

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Mortar[0]	-0.824133	0.088642	-9.30	<.0001*
DetInf	1.8527494	0.25045	7.40	<.0001*
conceal	0.0142896	0.003043	4.70	<.0001*
(conceal-50.0154)*(conceal-50.0154)	0.0005803	0.000129	4.50	<.0001*
inf	-0.357422	0.090285	-3.96	0.0002*
actDef	-1.084963	0.331238	-3.28	0.0019*
DetVeh	0.7833786	0.248505	3.15	0.0027*
EW	0.9975247	0.329208	3.03	0.0038*
(conceal-50.0154)*(EW-0.55001)	0.0246254	0.010991	2.24	0.0294*
(conceal-50.0154)*Mortar[0]*(actDef-0.55001)	0.0222999	0.010512	2.12	0.0388*
(conceal-50.0154)*(actDef-0.55001)	-0.021892	0.010454	-2.09	0.0412*
Mortar[0]*(actDef-0.55001)	0.6545445	0.333313	1.96	0.0550
(conceal-50.0154)*Mortar[0]	-0.002065	0.003062	-0.67	0.5031

Prediction Profiler

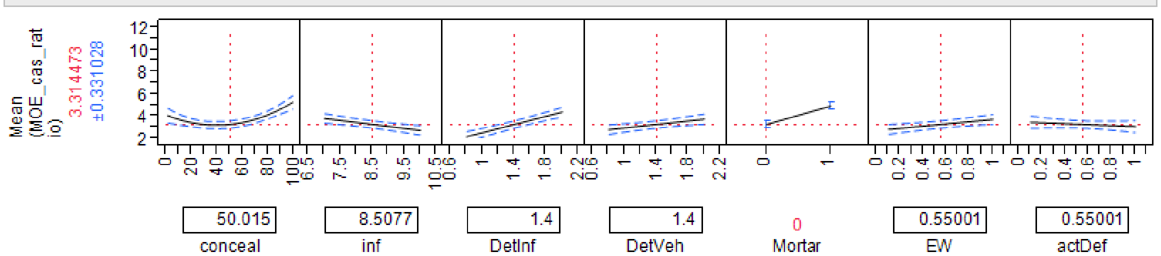
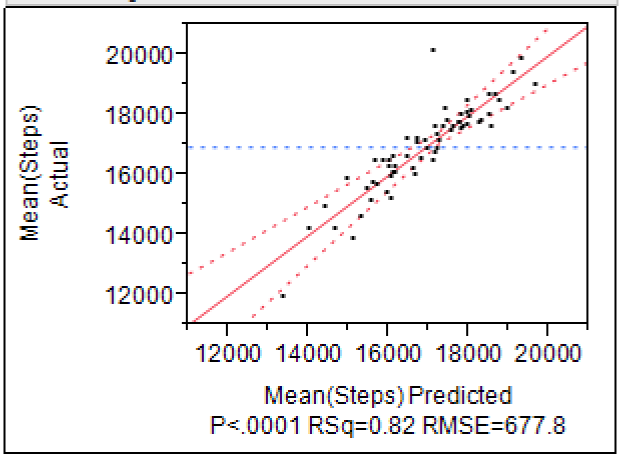


Figure 65. Advanced regression model for "casualty ratio" conducted on the MOE mean.

“Battle duration”

Actual by Predicted Plot



Summary of Fit

RSquare	0.81795
RSquare Adj	0.784237
Root Mean Square Error	677.8
Mean of Response	16917.05
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	17379.646	135.7595	128.02	<.0001*
#hits{1&2-3}	-306.8409	100.583	-3.05	0.0035*
#hits{1-2}	-435.6877	113.1296	-3.85	0.0003*
conceal	-1457.725	144.3558	-10.10	<.0001*
speed	-460.9755	145.3894	-3.17	0.0025*
DetInf	-594.2366	145.2946	-4.09	0.0001*
DetVeh	-994.9197	144.6723	-6.88	<.0001*
MG	-46.21124	194.366	-0.24	0.8130
Mortar[0]	320.54629	86.47147	3.71	0.0005*
Mortar[1]	-320.5463	86.47147	-3.71	0.0005*
#hits{1-2}*(MG-1.40002)	534.98622	209.6115	2.55	0.0136*
(conceal-50.0154)*(conceal-50.0154)	-1346.533	310.655	-4.33	<.0001*

Prediction Profiler

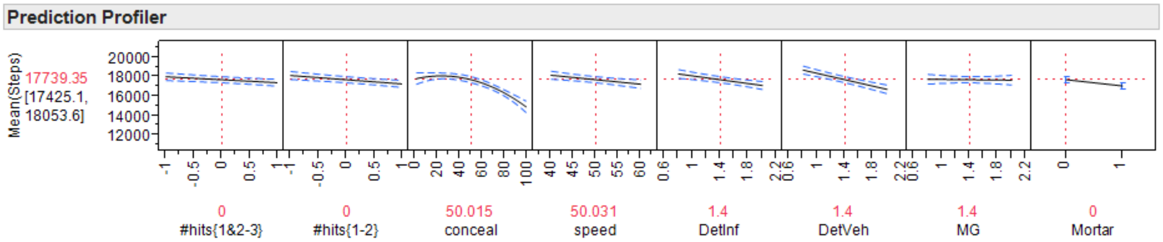
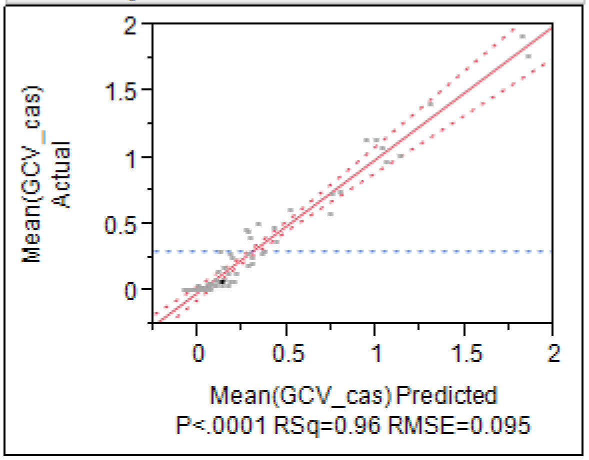


Figure 66. Advanced regression model for “battle duration” conducted on the MOE mean.

“GCV casualties”

Actual by Predicted Plot



Summary of Fit

RSquare	0.961977
RSquare Adj	0.952285
Root Mean Square Error	0.094962
Mean of Response	0.302441
Observations (or Sum Wgts)	65

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
#hits{3&2-1}	-0.412507	0.014691	-28.08	<.0001*
actDef	0.6334061	0.054117	11.70	<.0001*
(#hits{3&2-1}-0.50769)*(actDef-0.55001)	-0.740874	0.082272	-9.01	<.0001*
armor	-0.000469	5.852e-5	-8.01	<.0001*
(#hits{3&2-1}-0.50769)*(TOW-1.40002)	0.3636877	0.047683	7.63	<.0001*
TOW	-0.265966	0.03518	-7.56	<.0001*
(#hits{3&2-1}-0.50769)*(armor-650.031)	0.000406	6.266e-5	6.48	<.0001*
(TOW-1.40002)*(actDef-0.55001)	-0.91303	0.146157	-6.25	<.0001*
(#hits{3&2-1}-0.50769)*(TOW-1.40002)*(actDef-0.55001)	1.4747739	0.24193	6.10	<.0001*
conceal	-0.001721	0.000414	-4.16	0.0001*
#hits{3-2}	-0.056555	0.014566	-3.88	0.0003*
(conceal-50.0154)*Mortar[0]	-0.000992	0.000421	-2.36	0.0223*
Mortar[0]	0.0239758	0.012378	1.94	0.0583

Prediction Profiler

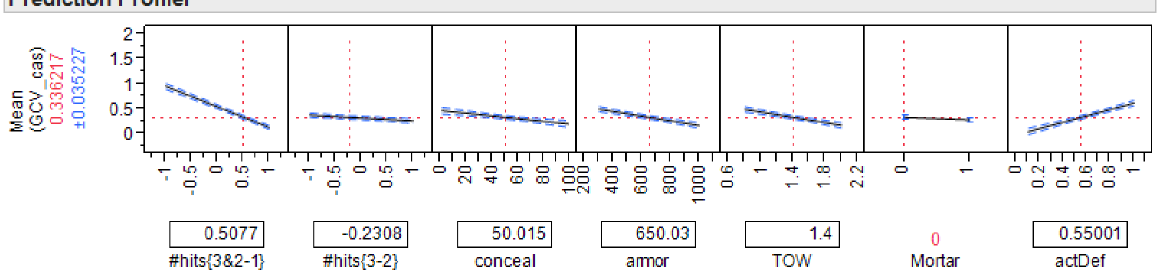


Figure 67. Advanced regression model for “CGV casualties” conducted on the MOE mean.

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APPENDIX G. "TANK GCV" MAIN EFFECT REGRESSION MODELS

The following regression models provide the underlying analysis results for the stated insights and conclusions in this study. Furthermore, this appendix contains additional information on the main effect models for further research. In each figure the "Actual vs. Predicted plot" is shown along with a "Pareto plot" which gives a visualization of how important the factor is for the model.

"BLUE casualties"

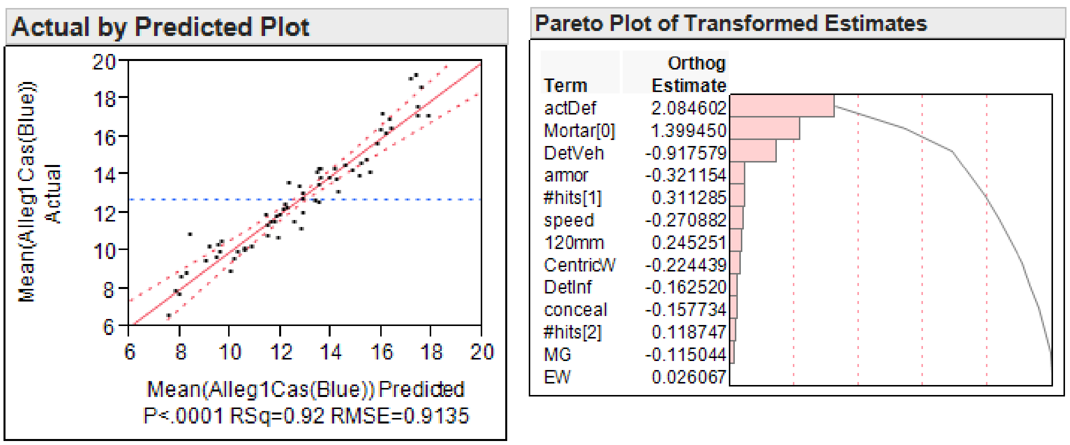


Figure 68. Additional graphs for the "BLUE casualties" MOE.

"RED casualties"

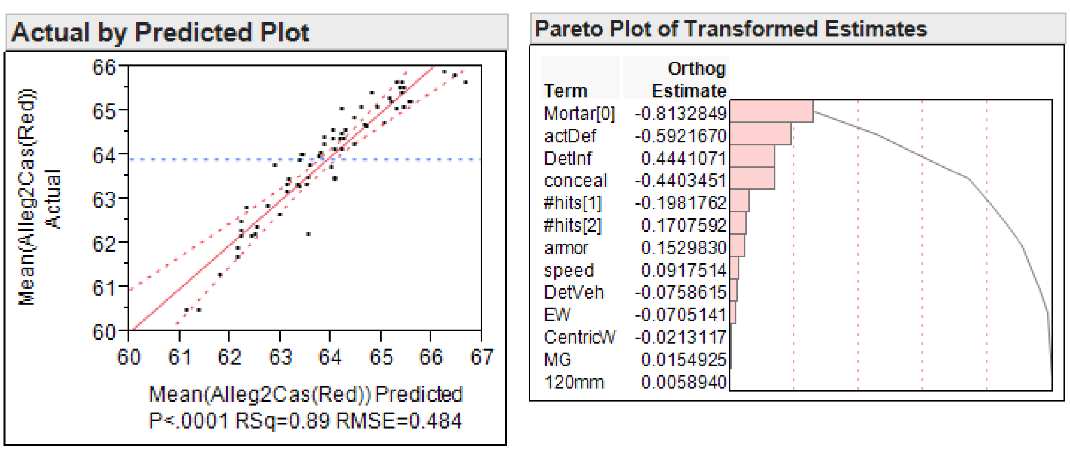


Figure 69. Additional graphs for the "RED casualties" MOE.

“Battle duration”

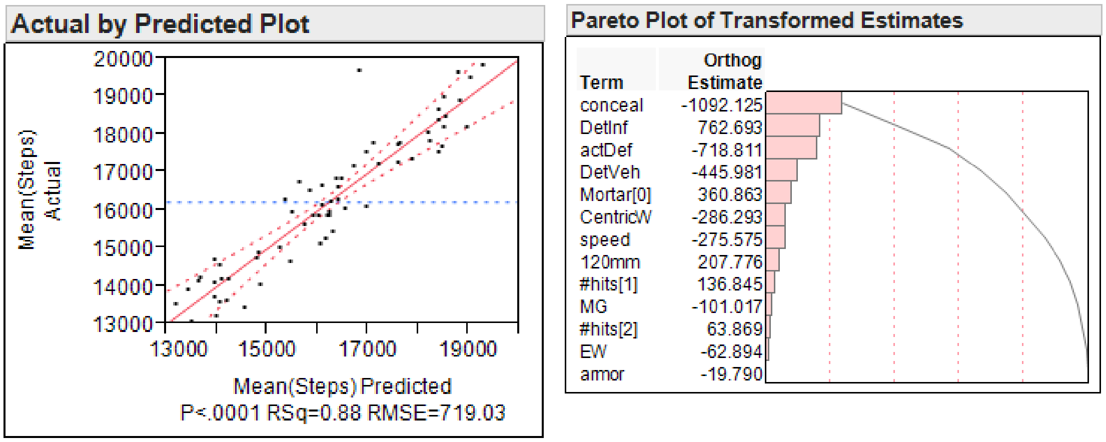


Figure 70. Additional graphs for the “Battle duration” MOE.

“Casualty ratio”

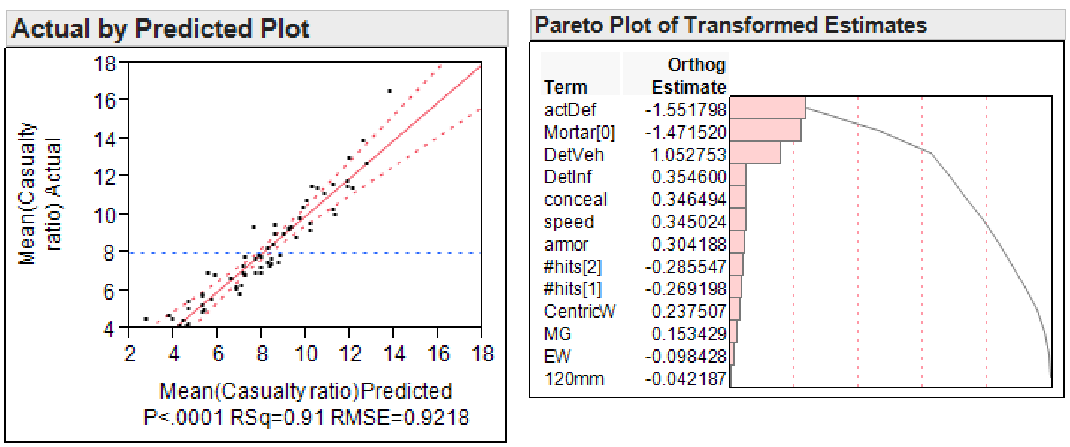
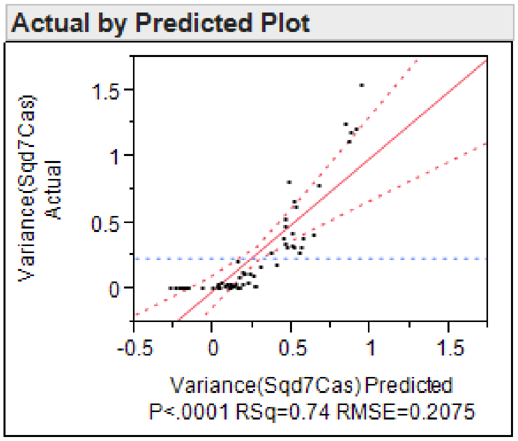


Figure 71. Additional graphs for the “Casualty ratio” MOE.

“GCV casualty”



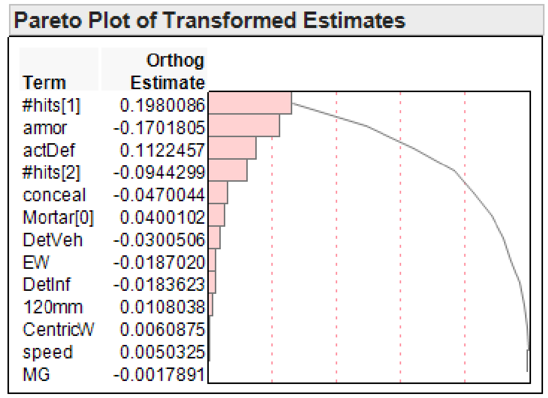


Figure 72. Additional graphs for the “GCV casualty” MOE.

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APPENDIX H. "TANK GCV" PARTITION TREES

The following graphs show the results for the partition tree models. They provide important factor thresholds and a picture of the split analysis process.

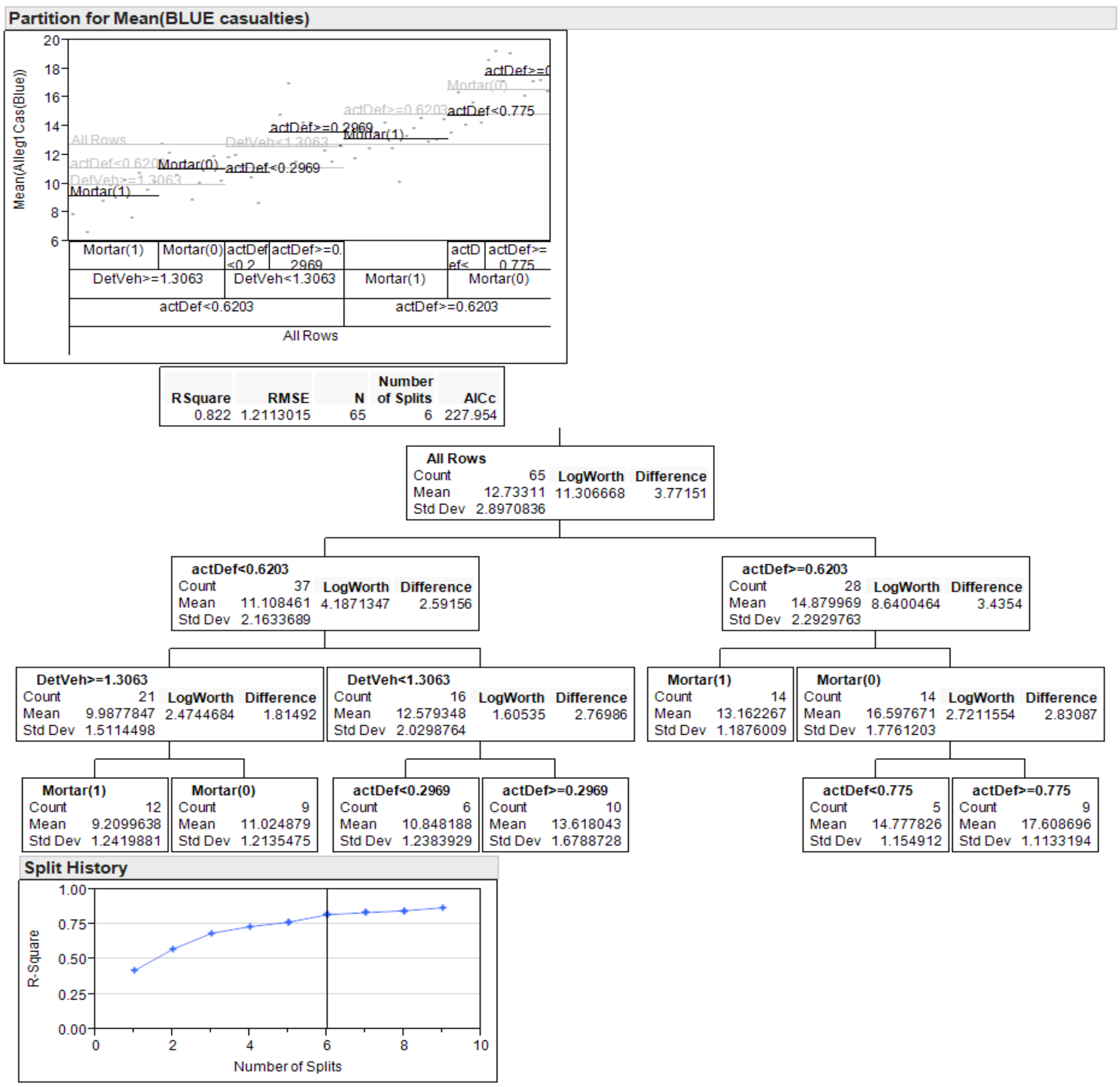


Figure 73. Partition tree and split history for the "BLUE casualties" MOE. The analysis is conducted on the mean "BLUE casualties".

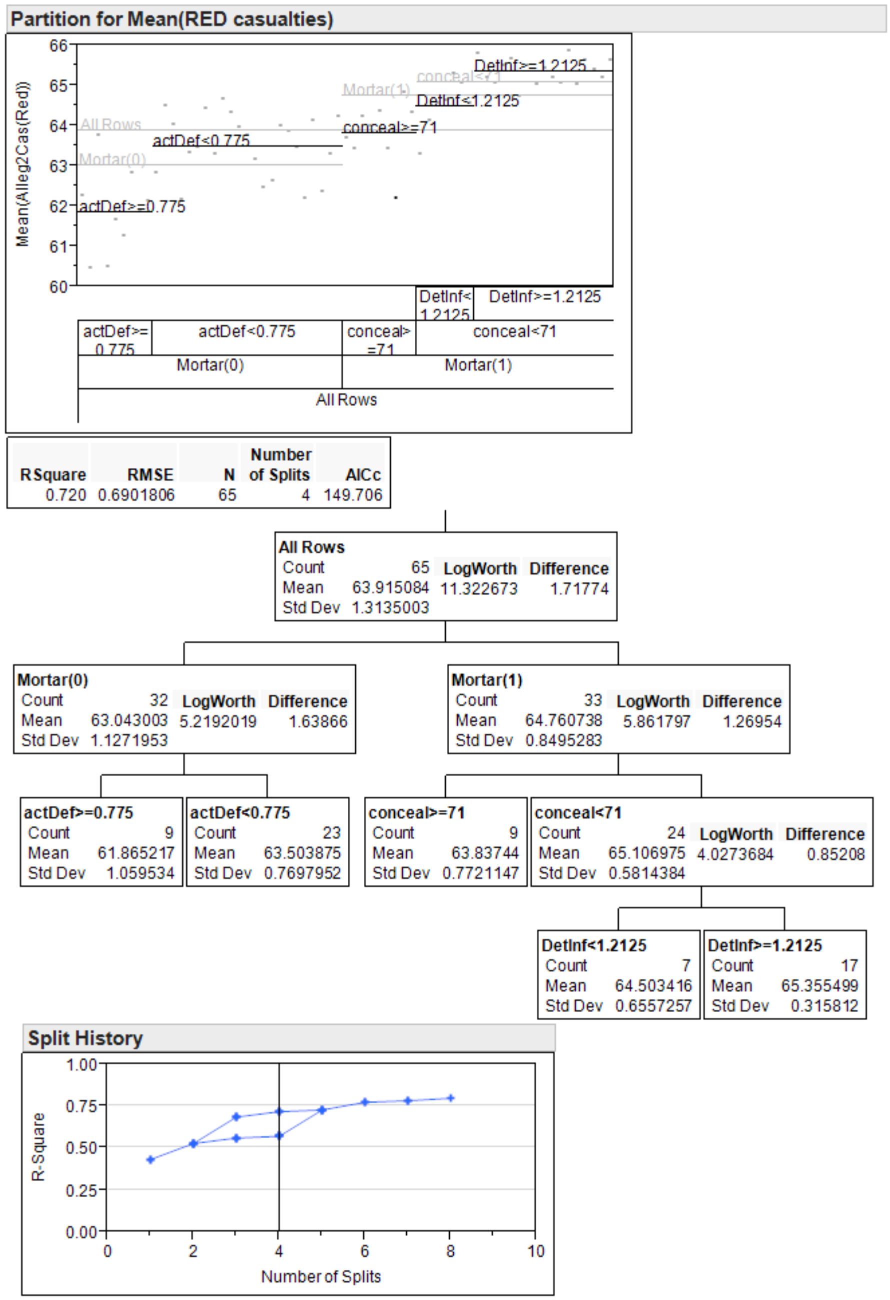


Figure 74. Partition tree and split history for the “RED casualties” MOE. The analysis is conducted on the mean “RED casualties.”

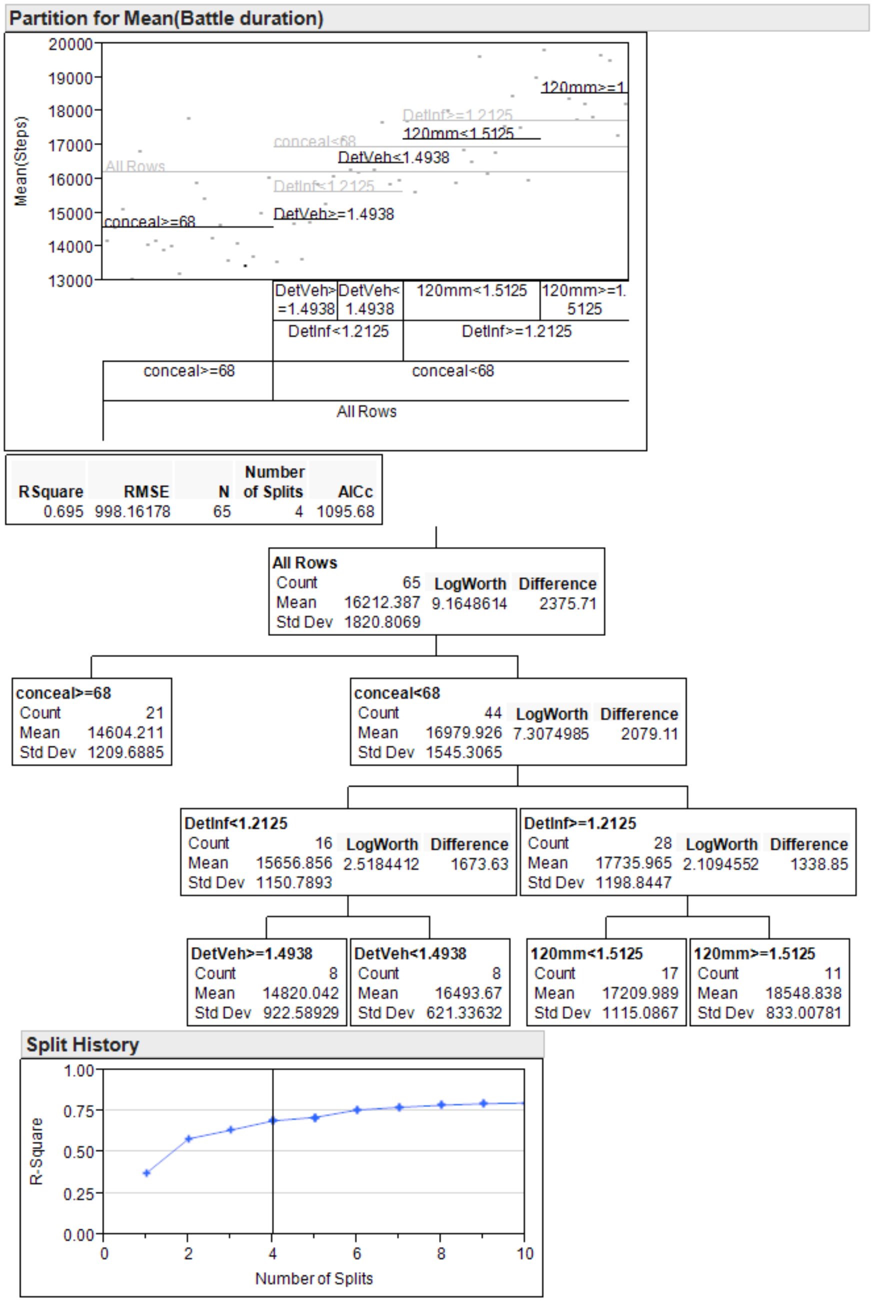


Figure 75. Partition tree and split history for the “Battle duration” MOE. The analysis is conducted on the mean “Battle duration.”

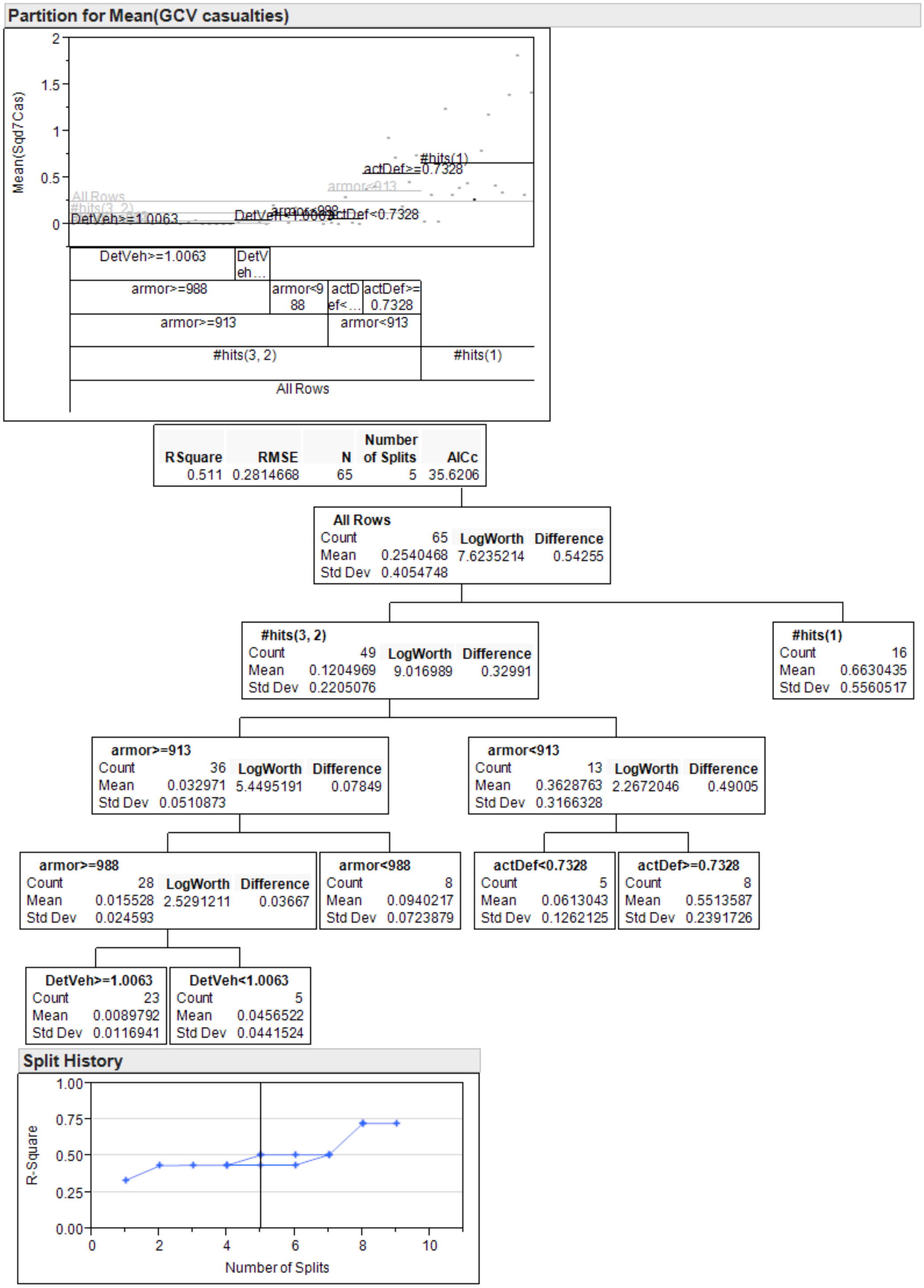


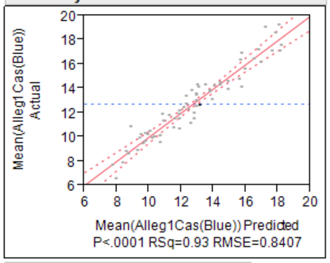
Figure 76. Partition tree and split history for the “GCV casualties” MOE. The analysis is conducted on the mean “GCV casualty.”

APPENDIX I. "TANK GCV" ADVANCED REGRESSION MODELS

The following results show the final regression model with interactions and non-linearities. They will be combined into the "dashboard" in future research and are the final analysis results of the conducted study. Each regression model is presented with its "actual observed vs prediction" plot to show how close the model is at the observed values. Furthermore, the "summary statistics" for the model are stated and the model itself is shown with each implemented factor. Finally, the "Prediction profiler" gives a graphical representation of how variable the model is for changes in each included main effect.

Response Mean(BLUE casualties)

Actual by Predicted Plot



Summary of Fit

RSquare	0.92632
RSquare Adj	0.915794
Root Mean Square Error	0.840683
Mean of Response	12.73311
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	12.74616	0.104314	122.19	<.0001*
actDef	3.550413	0.177982	19.95	<.0001*
Mortar[0]	1.3710861	0.104932	13.07	<.0001*
Mortar[1]	-1.371086	0.104932	-13.07	<.0001*
DetVeh	-1.603431	0.178244	-9.00	<.0001*
Mortar[0]*(actDef-0.55001)	0.5974887	0.17844	3.35	0.0015*
Mortar[1]*(actDef-0.55001)	-0.597489	0.17844	-3.35	0.0015*
#hits{3-2&1}	-0.346566	0.119156	-2.91	0.0052*
armor	-0.37654	0.178109	-2.11	0.0390*
speed	-0.349422	0.177356	-1.97	0.0538
CentricW	-0.346384	0.178214	-1.94	0.0570

Effect Screening

Using estimates standardized to have equal variances

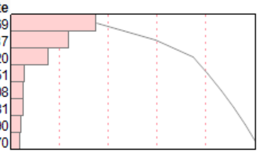
Using estimates orthogonalized to be uncorrelated

	Lenth PSE
t-Test Scale	4.664312
Coded Scale	0.4863661

Each Orthog Estimate is conditioned on the effects before it

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
actDef	2.079869
Mortar[0]	1.427187
DetVeh	-0.913520
Mortar[0]*(actDef-0.55001)	0.349151
armor	-0.324908
#hits{3-2&1}	-0.323581
speed	-0.271890
CentricW	-0.227470



Prediction Profiler

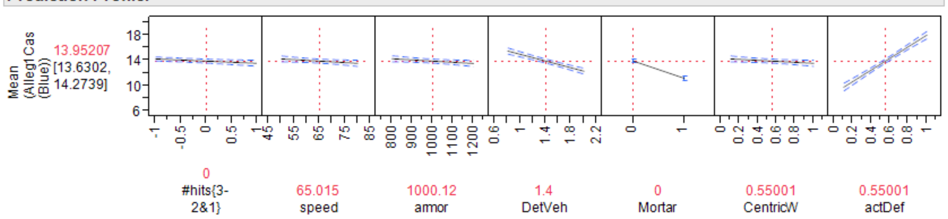
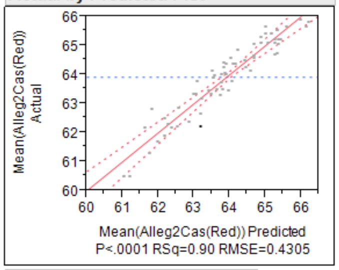


Figure 77. Advanced regression model for “BLUE casualties” conducted on the MOE mean.

Response Mean(RED casualties)

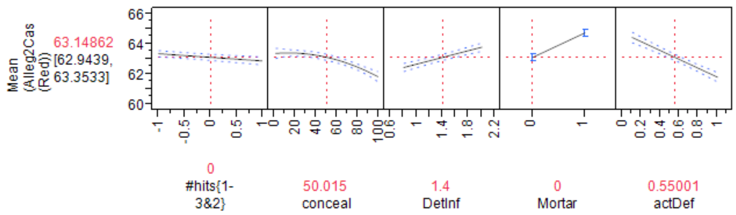
Actual by Predicted Plot



Summary of Fit

RSquare	0.904332
RSquare Adj	0.892584
Root Mean Square Error	0.430493
Mean of Response	63.91508
Observations (or Sum Wgts)	65

Prediction Profiler



Effect Screening

Using estimates standardized to have equal variances

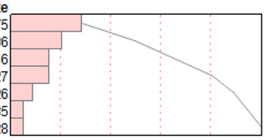
Using estimates orthogonalized to be uncorrelated

	Lenth PSE
t-Test Scale	12.387514
Coded Scale	0.661444

Each Orthog Estimate is conditioned on the effects before it

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Mortar[0]	-0.8248675
actDef	-0.5920236
DetInf	0.4422216
conceal	-0.4409627
#hits{1-3&2}	-0.2604826
(conceal-50.0154)*(conceal-50.0154)	-0.1543935
Mortar[0]*(actDef-0.55001)	-0.1537228



Scaled Estimates

Nominal factors expanded to all levels

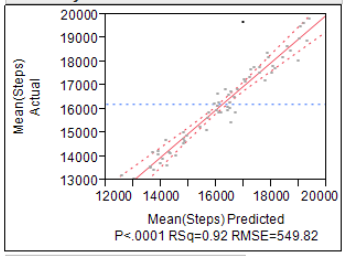
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	64.082733	0.081144	789.74	<.0001*
Mortar[0]	-0.811885	0.053705	-15.12	<.0001*
Mortar[1]	0.8118852	0.053705	15.12	<.0001*
actDef	-1.009697	0.091243	-11.07	<.0001*
conceal	-0.775281	0.091212	-8.50	<.0001*
DetInf	0.6777757	0.091262	7.43	<.0001*
#hits{1-3&2}	-0.240694	0.062843	-3.83	0.0003*
Mortar[0]*(actDef-0.55001)	-0.311635	0.093296	-3.34	0.0015*
Mortar[1]*(actDef-0.55001)	0.3116354	0.093296	3.34	0.0015*
(conceal-50.0154)*(conceal-50.0154)	-0.513047	0.177434	-2.89	0.0054*

Figure 78. Advanced regression model for “RED casualties” conducted on the MOE mean.

Response Mean(battle duration)

Actual by Predicted Plot



Summary of Fit

RSquare	0.923063
RSquare Adj	0.908816
Root Mean Square Error	549.8247
Mean of Response	16212.39
Observations (or Sum Wgts)	65

Scaled Estimates

Nominal factors expanded to all levels
Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	17022.782	158.8651	107.15	<.0001*
conceal	-1853.469	116.4776	-15.91	<.0001*
DetInf	1348.4825	116.5023	11.57	<.0001*
actDef	-1230.296	116.3948	-10.57	<.0001*
DetVeh	-818.1564	116.5411	-7.02	<.0001*
(conceal-50.0154)*(conceal-50.0154)	-1546.63	247.6839	-6.24	<.0001*
Mortar[0]	395.97867	68.65658	5.77	<.0001*
Mortar[1]	-395.9787	68.65658	-5.77	<.0001*
CentricW	-506.5666	116.5145	-4.35	<.0001*
speed	-410.0153	115.9537	-3.54	0.0008*
(DetInf-1.40002)*(DetInf-1.40002)	-795.7229	246.0521	-3.23	0.0021*
(conceal-50.0154)*(DetInf-1.40002)	-564.5516	245.5091	-2.30	0.0254*

Effect Screening

Using estimates standardized to have equal variances

Using estimates orthogonalized to be uncorrelated

	Lenth PSE
t-Test Scale	8.2223999
Coded Scale	560.74599

Each Orthog Estimate is conditioned on the effects before it

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
conceal	-1095.150
DetInf	769.872
actDef	-720.417
DetVeh	-445.417
Mortar[0]	381.115
(conceal-50.0154)*(conceal-50.0154)	-366.546
CentricW	-288.712
speed	-272.497
(DetInf-1.40002)*(DetInf-1.40002)	-220.548
(conceal-50.0154)*(DetInf-1.40002)	-133.700

Prediction Profiler

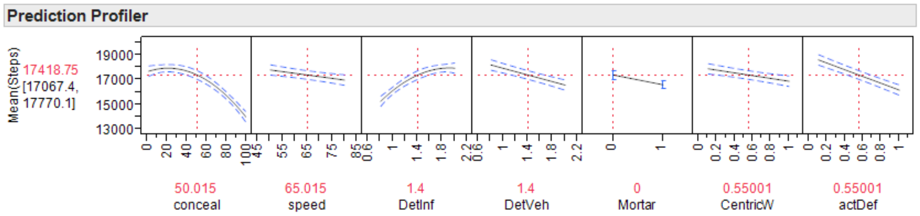
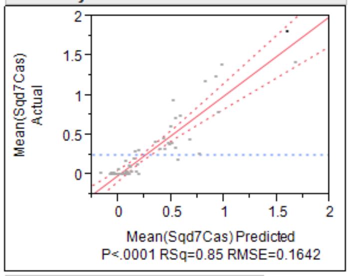


Figure 79. Advanced regression model for “Battle duration” conducted on the MOE mean.

Response Mean(GCV casulaties)

Actual by Predicted Plot



Summary of Fit

RSquare	0.85391
RSquare Adj	0.835969
Root Mean Square Error	0.16422
Mean of Response	0.254047
Observations (or Sum Wgts)	65

Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.2540191	0.020447	12.42	<.0001*
#hits{3&2-1}	-0.278459	0.023847	-11.68	<.0001*
armor	-0.438341	0.039801	-11.01	<.0001*
actDef	0.3377345	0.042191	8.00	<.0001*
#hits{3&2-1}*(armor-1000.12)	0.226657	0.039801	5.69	<.0001*
(armor-1000.12)*(actDef-0.55001)	-0.301449	0.057439	-5.25	<.0001*
#hits{3&2-1}*(actDef-0.55001)	-0.181338	0.042191	-4.30	<.0001*
#hits{3&2-1}*(armor-1000.12)*(actDef-0.55001)	0.0683473	0.057439	1.19	0.2390

Effect Screening

Using estimates standardized to have equal variances

Using estimates orthogonalized to be uncorrelated

	Lenth PSE
t-Test Scale	8.2012076
Coded Scale	0.1670505

Each Orthog Estimate is conditioned on the effects before it

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
#hits{3&2-1}	-0.2337124
armor	-0.1901797
actDef	0.1311151
#hits{3&2-1}*(armor-1000.12)	0.1113670
(armor-1000.12)*(actDef-0.55001)	-0.1100799
#hits{3&2-1}*(actDef-0.55001)	-0.0717127
#hits{3&2-1}*(armor-1000.12)*(actDef-0.55001)	0.0242373

Prediction Profiler

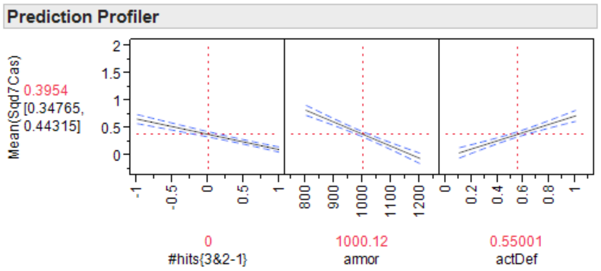


Figure 80. Advanced regression model for “BLUE casualties” conducted on the MOE mean.

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